

**TOWARDS IMPROVING CLINICAL EVALUATION OF THE SHOULDER:  
DEFINING UPPER LIMB BIOMECHANICS OF BREAST CANCER SURVIVORS  
DURING FUNCTIONAL EVALUATION TASKS**

A Thesis Submitted to the  
College of Graduate and Postdoctoral Studies  
in Partial Fulfillment of the Requirements  
for the Degree of Doctor of Philosophy  
in the Department of Health Sciences  
University of Saskatchewan  
Saskatoon

By

ANGELICA E. LANG

## **PERMISSION TO USE**

In presenting this thesis/dissertation in partial fulfillment of the requirements for a Postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis/dissertation in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis/dissertation work or, in their absence, by the Head of the Department or the Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis/dissertation or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis/dissertation.

## **DISCLAIMER**

Reference in this thesis/dissertation to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the University of Saskatchewan. The views and opinions of the author expressed herein do not state or reflect those of the University of Saskatchewan, and shall not be used for advertising or product endorsement purposes.

Requests for permission to copy or to make other uses of materials in this thesis/dissertation in whole or part should be addressed to:

Head of the College of Medicine

5D40 Health Sciences Building Box 19

Wiggins Road

University of Saskatchewan

Saskatoon, Saskatchewan S7N 5E5 Canada

OR

Dean

College of Graduate and Postdoctoral Studies

University of Saskatchewan

116 Thorvaldson Building, 110 Science Place

Saskatoon, Saskatchewan S7N 5C9 Canada

## **THESIS SUMMARY**

Breast cancer is the most commonly diagnosed cancer among women in Canada, and survivors are often affected by post-treatment upper limb sequelae. Some limitations, such as range of motion restrictions, strength reductions, and presence of pain, have been well documented in survivors but the definition of biomechanical changes following treatment are not as robust. Further, status as breast cancer survivor has been indicated as a risk factor for secondary rotator cuff disorders, but the causes of such secondary morbidity are unidentified. Characterization of biomechanical shoulder alterations could provide insight to the higher prevalence of rotator cuff disorders in breast cancer survivors.

Historically, scapular motion tracking has been difficult for biomechanists, and currently used strategies were developed and tested on young, unimpaired participants. The utility of current methods had not yet been tested in a pathological population. Therefore, the first study of this dissertation quantified error of the acromion marker cluster (AMC) in the study sample. Data were collected from 25 non-cancer controls and 25 post-mastectomy breast cancer survivors. Tracking the scapula with the AMC was most successful when using the double calibration method. This method resulted in errors of approximately 5-10° throughout full arm range of motion, with highest errors in scapular protraction. This error magnitude is within the previously reported range from younger populations, suggesting that the AMC is an acceptable strategy for tracking scapula in this sample.

The second study of this dissertation defined the upper limb kinematics of breast cancer survivors during return-to-work focused functional tasks. The motion of the torso, humeri and scapulae were tracked during six different functional tasks: overhead reach, repetitive reach, fingertip dexterity, hand and forearm dexterity, overhead lift, and overhead work. Mean,

maximum, and minimum values for each degree of freedom were extracted from each movement cycle and compared across groups. Post-hoc analyses determined that presence of impingement pain in breast cancer survivors, as determined by pain on at least one of three impingement provocation tests, was associated with clinical, performance, and kinematic differences. Breast cancer survivors with pain had higher disability scores, lower range of motion, and lower performance scores. During the overhead reach and overhead lift, scapular upward rotation was reduced at the top of the movements in the pain group. Additionally, at the extremes of the repetitive reach and overhead lift, breast cancer survivors with pain had reduced humeral abduction and humeral internal rotation. These compensations are associated with impingement pain diagnosis suggesting a potential link between biomechanical risk factors, pain, and future development of rotator cuff disorders.

A measure of muscle activation would clarify the influence of altered muscle force strategy on identified movement compensations, and this was the objective of the third study. Motion data from the six functional tasks were used as input for a biomechanical model. A modified version of the Shoulder Loading Analysis Module (SLAM) was used to estimate individual muscle forces. The model was modified to accept measured scapular orientations, then pectoralis capacity adjustment for breast cancer survivors was tested to determine the best strategy for modelling this group. Model outputs were compared to measured electromyography (EMG) from select muscles to assess model efficacy, and then maximum muscle forces for each task were compared between the three groups. Model outputs with these participants, task parameters, and modifications differed from experimental EMG, but within accepted error ranges. Maximum forces during task performance differed for the breast cancer survivors with pain: upper trapezius, supraspinatus and pectoralis major muscles were consistently higher for this group,

suggesting that rehabilitation should focus on preventing potentially harmful scapular and humeral kinematics by reducing activity in several key muscles, notably the upper trapezius and supraspinatus.

To determine the applicability of these data for current biomechanical and clinical practice and arm assessments, the relationship of scapular motion during arm elevation and functional tasks was evaluated. While alterations were identified during functional tasks, it is not clear if these same alterations are present in arm elevations, even though this is the prevailing scapular motion assessment method. First, scapular upward rotation at five levels of arm elevation was compared between the three groups, and then the correlation of upward rotation and scapulohumeral rhythm (SHR) in both types of motion at corresponding arm elevation levels was assessed. Decrements in upward rotation were identified in the pain group, but at lower arm elevations. Upward rotation was moderately to strongly correlated between the two types of movements, but SHR did not demonstrate the same strength and significant relationships. Overall, sagittal arm elevation was most strongly correlated with functional task performance, but the differing results from the group comparisons and inconsistency of the SHR relationship suggest that a simple functional task could be a more robust clinical assessment method.

These studies combine to enhance both fundamental and clinical definitions of post-treatment shoulder dysfunction in breast cancer survivors. Shoulder kinematics, as measured by the AMC, are altered in breast cancer survivors with impingement-related pain, and subsequent muscle force predictions highlighted important compensatory muscle strategies that could be targeted in rehabilitation to treat dysfunction and prevent rotator cuff disorders in this population. Finally, while evaluation during arm elevation is the predominant method both in laboratory and clinical

evaluations, a loaded reach is recommended for improved assessment of scapular motion for return-to-work focused rehabilitation.

## **ACKNOWLEDGEMENTS**

First and foremost, I would like to thank my supervisors, Drs. Clark Dickerson, Soo Kim, and Steve Milosavljevic for their continual guidance and support throughout this degree. I am so glad I got to work closely with each of you, and I am a better researcher (and person) as a result.

Second, my powerhouse advisory committee were also essential to every step of this thesis: Drs. Joel Lanovaz, Ian Stavness, and Catherine Trask. Each of you have been an integral part of this process, and I am very fortunate to have had the opportunity to learn from you.

I would also like to recognize to the Natural Sciences and Engineering Research Council for their financial assistance with this project.

Thank you to all the members of the Ergonomics Lab and DIESEL-ites who supported me along the way, and particularly Jamie Stobart, Lia Tennant, and Suelen Goes for their help with data collection. I also leaned heavily on Aaron Kocielek, Marcus Yung, and Dave Kingston for advice and truly appreciate their guidance. Most importantly, thank you to each of you for your friendship!

I want to acknowledge both of my sets of parents, Doug and Shelley Lang (Mom and Dad) and Alan and Julie Schemenauer, for their love and encouragement (even if the details of my work were a little unclear) and their never-ending help with my son, Connor.

Finally, last but certainly not least, I want to thank my husband, Colby Schemenauer. You have been an unwavering pillar of support throughout not only this degree, but my whole adult life. Thank you.

## TABLE OF CONTENTS

PERMISSION TO USE.....	i
THESIS SUMMARY.....	ii
ACKNOWLEDGEMENTS.....	vi
LIST OF TABLES.....	x
LIST OF FIGURES.....	xi
CHAPTER 1: INTRODUCTION.....	1
1.1 Motivation.....	1
1.2 Overarching Research Aim.....	2
1.3 Outline of Dissertation Document.....	4
CHAPTER 2: LITERATURE REVIEW.....	6
2.1 Breast cancer and arm function.....	6
2.1.1 Overview of Breast cancer.....	6
2.1.2 Breast cancer surgeries and treatments.....	8
2.1.3 Arm morbidities and breast cancer treatment.....	12
2.1.4 Biomechanics and Breast cancer.....	19
2.1.4 Correlation with Quality of Life.....	22
2.1.5 Return-to-work in breast cancer survivors.....	23
2.3 Overview of modelling methods and approach.....	26
2.3.1 Modelling pathological shoulders.....	26
2.3.2 Biomechanical modelling fundamentals.....	27
2.4 Clinical evaluation of the shoulder.....	30
2.4.1 Thoracohumeral Motion Clinical Assessment.....	30
2.4.2 Scapular Motion Clinical Assessment.....	31
2.5 Literature Review Conclusion.....	34
CHAPTER 3: THE UTILITY OF THE ACROMION MARKER CLUSTER (AMC) IN A CLINICAL POPULATION.....	36
3.1 Abstract.....	37
3.2 Introduction.....	38
3.3 Methods.....	40
3.3.1 Participants.....	40
3.3.2 Instrumentation.....	41
3.3.3 Procedure.....	43



3.3.4 Analysis .....	44
3.4 Results.....	46
3.4.1 Calibration and elevation interaction .....	46
3.4.2 Calibration and group .....	49
3.5 Discussion .....	50
3.6 Conclusions.....	54
TRANSITION FROM CHAPTER 3 TO CHAPTER 4 .....	55
CHAPTER 4: IMPINGEMENT PAIN AFFECTS KINEMATICS OF BREAST CANCER SURVIVORS IN WORK-RELATED FUNCTIONAL TASKS.....	56
4.1 Abstract .....	57
4.2 Introduction .....	58
4.3 Methods .....	60
4.3.1 Participants .....	60
4.3.2 Instrumentation .....	60
4.3.3 Experimental Protocol .....	61
4.3.4 Data Processing .....	64
4.3.5 Statistical Analysis .....	65
4.4 Results.....	65
4.4.1 Breast cancer survivors vs controls .....	67
4.4.2 Impingement pain vs controls .....	68
4.5 Discussion .....	73
4.6 Conclusions.....	79
TRANSITION BETWEEN CHAPTER 4 AND CHAPTER 5 .....	80
CHAPTER 5: ESTIMATING MUSCLE FORCES FOR BREAST CANCER SURVIVORS DURING FUNCTIONAL TASKS.....	81
5.1 Abstract .....	82
5.2 Introduction .....	84
5.3 Methods .....	86
5.3.1 Participants .....	86
5.3.2 Procedures.....	86
5.3.3 Data analysis .....	88
5.3.4 Statistical Analysis .....	89
5.4 Results.....	91
5.4.1 Comparison to EMG .....	91

5.4.2 Group Comparisons .....	92
5.5 Discussion .....	94
5.6 Conclusions.....	97
<b>TRANSITION FROM CHAPTER 5 TO CHAPTER 6 .....</b>	<b>99</b>
<b>CHAPTER 6: EXAMINING ASSESSMENT METHODS OF SCAPULAR MOTION: IS ARM ELEVATION ENOUGH? .....</b>	<b>100</b>
6.1 Abstract .....	101
6.2 Introduction .....	103
6.3 Methods .....	105
6.3.1 Participants .....	105
6.3.2 Experimental Procedures .....	106
6.3.3 Data analysis .....	108
6.3.4 Statistical analysis .....	110
6.4 Results.....	111
6.5 Discussion .....	118
6.6 Conclusion .....	121
<b>CHAPTER 7: CONCLUSIONS.....</b>	<b>122</b>
7.1 Limitations .....	125
7.2 Future Research Recommendations .....	126
7.3 Implications .....	127
<b>REFERENCES .....</b>	<b>128</b>
<b>APPENDIX A: LETTERS OF COPYRIGHT PERMISSON .....</b>	<b>147</b>
<b>APPENDIX B: INFORMATION AND CONSENT FORM .....</b>	<b>149</b>
<b>APPENDIX C: QUICK DISABILITIES OF ARM, SHOULDER AND HAND (QuickDASH) .....</b>	<b>157</b>

## LIST OF TABLES

<b>Table 3.1:</b> Participant demographics.....	41
<b>Table 3.2:</b> Landmark locations of anatomical markers.....	42
<b>Table 3.3:</b> RMSE in degrees at each elevation level.....	49
<b>Table 3.4:</b> Comparison of studies that have investigated the accuracy of the AMC method.....	52
<b>Table 4.1:</b> Order of task performance for each collection.....	62
<b>Table 4.2:</b> Participant demographic and clinical information.....	66
<b>Table 4.3:</b> Performance results.....	67
<b>Table 4.4:</b> Summary of kinematic differences between three groups.....	73
<b>Table 5.1:</b> Overall concordance ratios for each muscle by group.....	92
<b>Table 6.1:</b> Demographic information and clinically relevant variables.....	106
<b>Table 6.2:</b> Summary of scapular outcomes.....	110
<b>Table 6.3:</b> Strength of linear correlation ( $r$ ) for scapular upward rotation angle.....	114
<b>Table 6.4:</b> Strength of linear correlation ( $r$ ) for scapulohumeral rhythm.....	117

## LIST OF FIGURES

<b>Figure 1.1:</b> An outline of the specific goals and outcomes.....	5
<b>Figure 2.1:</b> Diagram of size classifications of primary tumor for breast cancer staging.....	8
<b>Figure 2.2:</b> Illustration of the affected tissues and surgical area for breast conserving surgery.....	9
<b>Figure 2.3:</b> Illustration of the affected tissues and surgical area for mastectomy.....	10
<b>Figure 3.1:</b> Marker set up of the upper body.....	42
<b>Figure 3.2:</b> Digitization of the inferior angle of the scapula at neutral.....	44
<b>Figure 3.3:</b> Mean error at 90° and maximum arm elevation for all participants.....	47
<b>Figure 3.4:</b> Absolute mean error for protraction, rotation, and tilt.....	48
<b>Figure 4.1:</b> Minimum, mean and maximum torso flexion/extension during the overhead lift....	68
<b>Figure 4.2:</b> Maximum scapular upward rotation for the overhead reach and lift tasks.....	69
<b>Figure 4.3:</b> Mean waveforms for humeral angles.....	72
<b>Figure 4.4:</b> Variance of upward rotation of the right and left scapulae.....	77
<b>Figure 5.1:</b> Mean differences between muscle forces and muscle activity.....	91
<b>Figure 5.2:</b> Peak predicted forces of muscles.....	93
<b>Figure 6.1:</b> Arm elevation in the sagittal plane guided by a rigid pole.....	108
<b>Figure 6.2:</b> Scapular upward rotation throughout arm elevation.....	112
<b>Figure 6.3:</b> Scapular upward rotation angle at 90° .....	115

## **CHAPTER 1: INTRODUCTION**

### **1.1 Motivation**

Breast cancer is the most frequently diagnosed cancer in women in Canada; an estimated one in nine Canadian women are diagnosed with breast cancer in their lifetime (Canadian Cancer Society, 2015). Fortunately, the survival rate following breast cancer diagnosis is almost 90% (Canadian Cancer Society, 2015). With this high rate of survival comes a rise in the prevalence of upper limb morbidities among survivors, including pain, swelling, decreased range of motion, and decreased strength (Hack, Cohen, Katz, Robson, & Goss, 1999; Kuehn et al., 2000). These symptoms may persist for years following treatment (Sagen et al., 2009), indicating an overall decreased function and quality of life after treatment, as well as an increased potential for future upper limb injury.

Many physical side effects of breast cancer treatment, such as pectoralis shortness, lymphoedema, and pain, have been associated with other upper limb disorders (Ebaugh, Spinelli, & Schmitz, 2011; Stubblefield & Keole, 2014; Yang et al., 2010). In particular, rotator cuff disease is strongly associated with breast cancer treatment and many of the subsequent physical changes (Ebaugh et al., 2011), including potential biomechanical adaptations at the shoulder (Borstad & Szucs, 2012; Brookham, Cudlip, & Dickerson, 2018a; Shamley, Srinaganathan, Oskrochi, Lascurain-Aguirrebeña, & Sugden, 2008). It is not clear, however, what kinematic and kinetic changes occur, and remain, following breast cancer treatment, particularly during functional tasks. This knowledge gap is notable, since aberrations in motion and muscle loading strategies during daily activities at home or work have the potential to lead to further injury, disability, and decreased function in many aspects of life.

Following treatment for any type of cancer, survivors are less likely to be employed for pay compared to non-cancer controls (Nitkin & Schultz, 2011). Return-to-work at an appropriate time, in a meaningful and capable manner is associated with increased quality of life (Anderson & Armstead, 1995). However, premature return-to-work can precipitate further injury; for breast cancer survivors in particular, persistent arm impairments suggests there are kinematic changes that could be exacerbated by work if they are not identified and treated. Currently, these alterations are poorly understood, suggesting the need for improved characterization of motion for evaluation and rehabilitation following breast cancer surgery.

This research addressed the current lack of knowledge regarding breast cancer survivor shoulder kinematics and kinetics, particularly in functional, work-related tasks. To this author's knowledge, no other investigations have attempted to define the biomechanical changes following breast cancer surgery in the context of return-to-work. Defining how and why shoulder motion is affected in functional tasks after breast cancer treatment will inform treatment and rehabilitation for return-to-work, while determining the most functionally relevant strategy for evaluating shoulder function will inform clinical practice for assessing pathological biomechanics.

## **1.2 Overarching Research Aim**

The overall objective of the proposed research was to improve the definition of shoulder biomechanics of breast cancer survivors. A combined approach including *in vivo* measurements, musculoskeletal modeling, and statistical approaches facilitated meeting this objective. These three techniques worked together to provide a novel understanding of shoulder biomechanics of breast cancer survivors that can inform clinical assessment, treatment, and return-to-work recommendations.

There were four specific research questions for this thesis:

1. Can the scapulae of breast cancer survivors and age-group-matched controls be tracked with sufficient accuracy using an acromial marker cluster (AMC)?

*Hypothesis: Errors from the AMC will be similar to those reported in previous work.* There is some error expected when comparing dynamic motion tracked with AMC to landmark palpation (used in the place of the less feasible method of bone pins), but the magnitudes of the errors will likely be similar to those reported in other investigations (Karduna, McClure, Michener, & Sennett, 2001; Maclean, Chopp, Grewal, Picco, & Dickerson, 2014; van Andel, van Hutten, Eversdijk, Veeger, & Harlaar, 2009). Acceptable error levels (5-10°) will indicate the utility of using the AMC to track the scapula in the following investigations.

2. Are torso and shoulder kinematics during arm-centric functional task performance different for breast cancer survivors than non-cancer controls?

*Hypothesis: Breast cancer survivors will use different kinematic strategies than controls.* Specifically, it is hypothesized that breast cancer survivors will decrease the contribution of the shoulder and increase torso range of motion to perform functional tasks (Lomond & Côté, 2011), as well as increase protraction of the scapula due to pectoralis tightness (Borstad & Szucs, 2012).

3. Are muscle force strategies different for breast cancer survivors than age-group-matched controls?

*Hypothesis: Breast cancer survivors will have different muscle loading strategies than the control group.* It is expected that breast cancer survivors and controls will use different kinematic strategies during both the arm elevations and the

functional tasks (Borstad & Szucs, 2012; Brookham, 2014), suggesting that there will also be differences in muscle load sharing strategies.

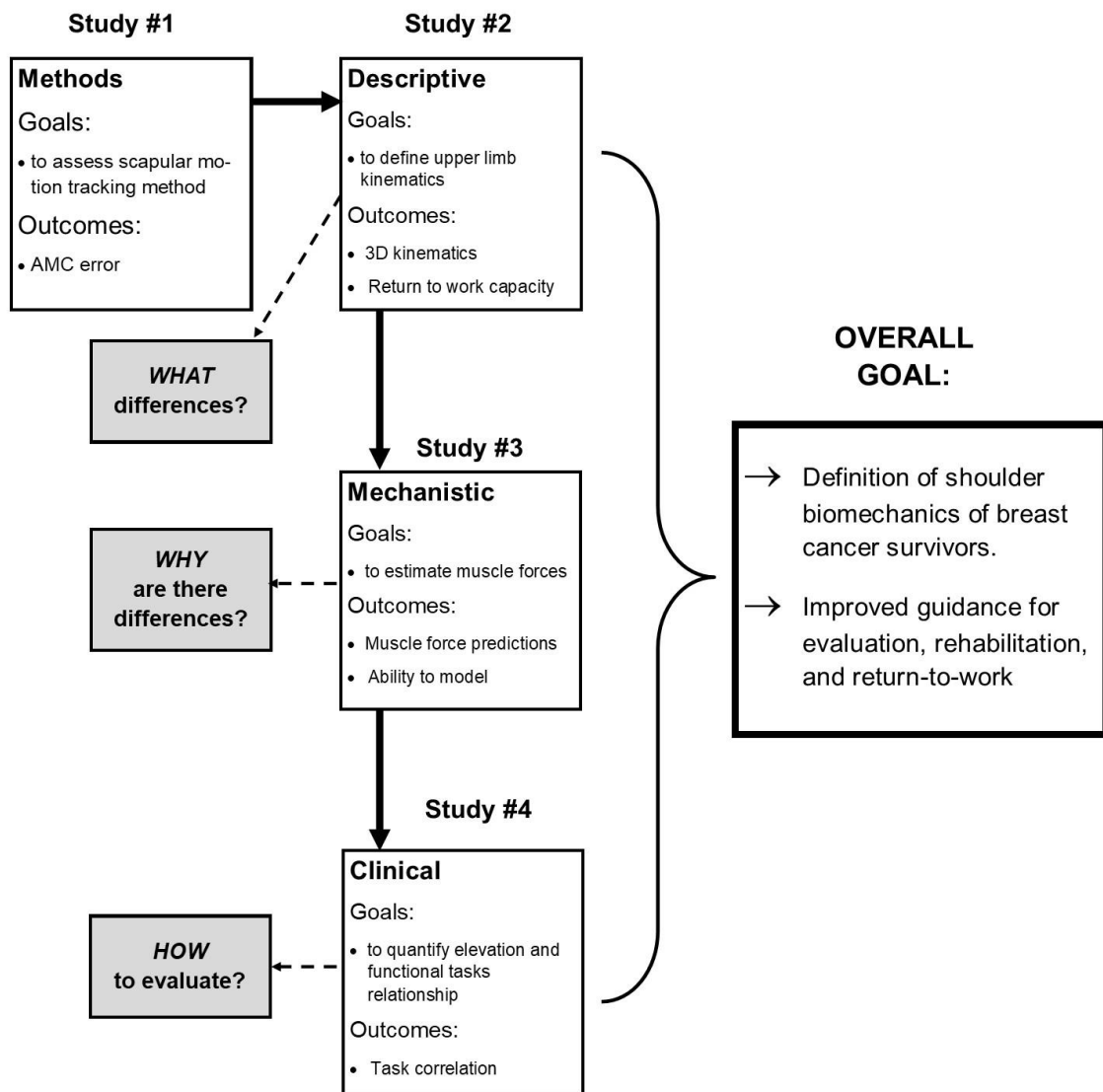
4. Is scapular motion during arm elevation associated with scapular motion in functional tasks for breast cancer survivors and non-cancer controls?

*Hypothesis: There will be a moderate relationship between scapular kinematics during arm elevations and WRF tasks.* Specifically, kinematics from scapular and frontal plane elevation will best predict kinematics during the dexterity tasks, while elevation in the sagittal plane will best predict kinematics during the overhead reach and overhead lift.

### **1.3 Outline of Dissertation Document**

This dissertation is comprised of a review of the literature to provide background, followed by manuscripts for four independent studies. The overall outline and relationship between the studies is illustrated in Figure 1.1. First, the accuracy of the AMC, the method used to track 3D motion of the scapula, was evaluated in Study #1. Kinematic data of the shoulder and torso were then examined in Study #2 to define and compare movement strategies of breast cancer survivors and non-cancer controls. These data were used as inputs for a musculoskeletal model of the shoulder to estimate and quantify muscular strategies in Study #3. Finally, Study #4 assessed the relationship of scapular kinematics between basic arm elevations and work-related functional tasks. Together, these four studies aimed to improve assessment and subsequent treatment of the shoulder following breast cancer treatment.





**Figure 1.1: An outline of the specific goals and outcomes of the four studies that comprise this thesis. All four studies use the same data collection. Shaded boxes indicate general study purposes.**

## **CHAPTER 2: LITERATURE REVIEW**

This review summarizes relevant literature relating to arm dysfunction and breast cancer, shoulder modeling, and clinical assessment of the shoulder. The first section of this literature review provides an overview of breast cancer and concomitant arm morbidities experienced after curative treatment. It then explores the current state of knowledge about biomechanical changes following surgical and adjunctive breast cancer treatment (e.g. radio and chemotherapy). A brief discussion of return-to-work following cancer ensues. The next section provides an overview of the fundamentals of musculoskeletal modeling, with special focus on the shoulder mechanism. Finally, the last section reviews the current strategies for shoulder evaluation in a clinical setting.

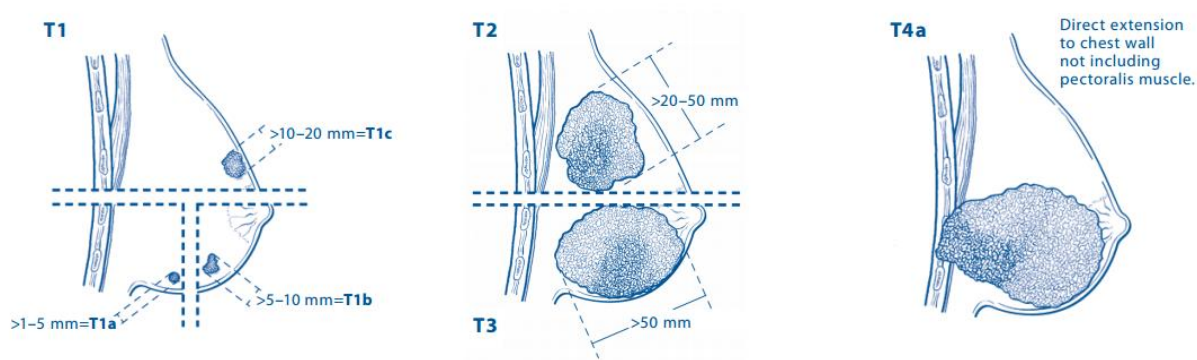
### **2.1 Breast cancer and arm function**

#### ***2.1.1 Overview of Breast cancer***

Breast cancer is the most common type of cancer experienced by women. It was expected that approximately 25,700 women in Canada would be diagnosed with breast cancer in 2016. This proportion represents 26% of all new cancer cases in women and is more than double the next most common cancer in women (lung cancer) (Canadian Cancer Society, 2015). Breast cancer in women between the ages of 50 and 69 comprises 52% of all cases, while women under the age of 50 account for 18% of breast cancer cases. Survival rates following breast cancer treatment are very high, however, with an average of 87% 5-year survival (Canadian Cancer Society, 2016). If the cancer is detected early, in stage 0 or I, the survival rate is 100%. For stage II, III, and IV, the 5-year survival rates are 86%, 57%, and 20%, respectively (Canadian Cancer Society, 2015, 2016).

Women between the ages of 50-69 most commonly experience breast cancer. The cause(s) of breast cancer is/are not yet completely known, but exposure to female hormones, such as estrogen and progesterone, is linked the development and growth of some breast cancer (Canadian Cancer Society, 2016). Other genetic and environmental factors are also believed to influence the development of breast cancer, such as family history, gene mutations, exposure to radiation, oral contraceptives, alcohol, smoking, and body weight (Canadian Cancer Society, 2016). However, it is difficult to determine the contribution of different individual factors with any certainty, as breast cancer can develop in women who do not have any of the risk factors listed above.

The stage of breast cancer development has implications for treatment strategy. Breast cancer stage is indicated by levels from 0 to IV as developed by the American Joint Committee on Cancer and International Union against Cancer (AJCC, 2009) (Figure 2.1). Cancer stage is determined according to the diameter or size of the primary tumour, the number of lymph nodes involved with the tumour, and the presence of distant metastases (Carter, Allen, & Henson, 1989) (Figure 2.1). Stage, and subsequent treatment strategy, affect intensity and prevalence of upper limb sequela, which will be further discussed in the next section.



**Figure 2.1: Diagram of size classifications of primary tumor for breast cancer staging (Canadian Cancer Society, 2015). T1 corresponds to Stage 1, T2 to Stage 2, etc.**

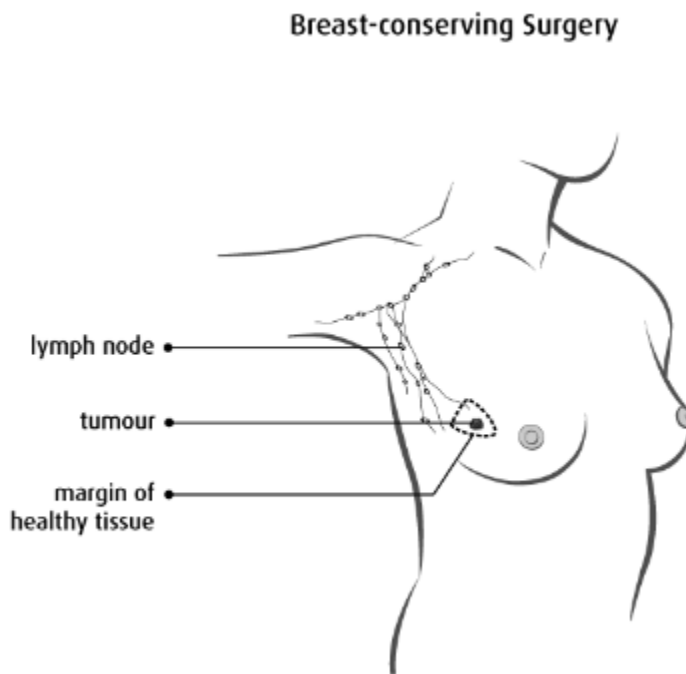
For the purposes of this proposal and literature review, individuals who have completed surgical treatment for breast cancer are termed *survivors* (Brookham, 2014).

### **2.1.2 Breast cancer surgeries and treatments**

Breast cancer typically is treated with surgery. The purposes of the surgery can include: to cure the cancer by removing the tumour, to determine if the cancer has spread to the lymph nodes, or to treat recurrence (Canadian Cancer Society, 2016). Breast cancer surgery options are breast conserving surgery, mastectomy, sentinel lymph node biopsy, and axillary node dissection. The type of surgery is determined by several factors including the size and location of the tumour, if the cancer has spread to the lymph nodes, and the overall health of the woman (Canadian Cancer Society, 2016).

Breast conserving surgery, sometimes called a lumpectomy, is the least invasive surgical option. It involves removing the tumour but keeping healthy breast or axilla tissue surrounding it (Canadian Cancer Society, 2016) (Figure 2.2). This conservative surgery is often followed by radiation therapy to the involved breast and regional lymph nodes (Haffty et al., 1989; Schmidt-

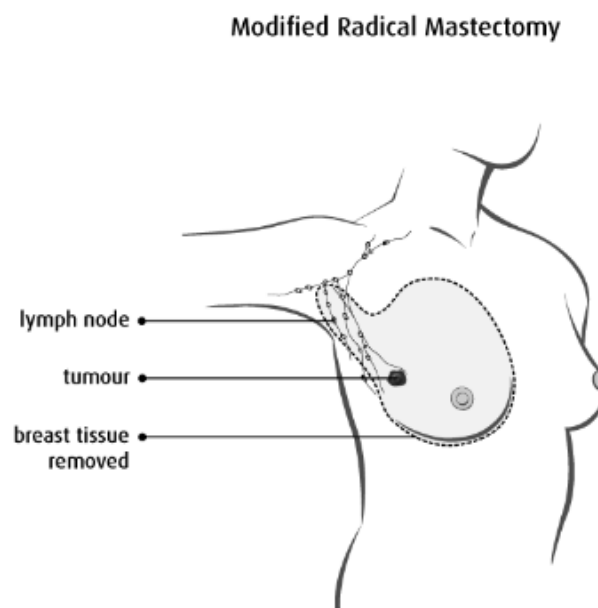
Ullrich et al., 1989). Breast conserving surgery allows a woman to conserve as much healthy breast tissue as possible and is an option if the tumour is small enough to remove all the cancer safely (Canadian Cancer Society, 2016). Survival rates are high and recurrence rates are low following breast conserving surgery, particularly for lower stage cancer (Haffty et al., 1989; Schmidt-Ullrich et al., 1989).



**Figure 2.2: Illustration of the affected tissues and surgical area for breast conserving surgery(Canadian Cancer Society, 2015).**

Mastectomy is another surgical option for breast cancer treatment. A mastectomy involves removing the entire affected breast. The radical mastectomy, as introduced by Halsted, is an operation that removes the breast, overlying skin, pectoralis major muscle, and requires extensive lymph node dissection (Halsted, 1894). The modified radical mastectomy (MRM) was later introduced to reduce the invasiveness of the radical mastectomy (Figure 2.3); the MRM

conserves the pectoralis muscle but removes the adjacent fascia (Patey & Dyson, 1948). The effect of preserving the pectoral fascia has also been previously investigated, and neither the removal nor the preservation of the fascia had an effect of recurrence or distant metastases 11 years post-surgery (Dalberg, Krawiec, & Sandelin, 2010). Still, those with the preserved fascia had an odds ratio of 1.8 for recurrence, suggesting there is a slight increase in risk to keeping this tissue (Dalberg et al., 2010); however, the effects of removing the fascia on the occurrence of arm morbidities was not considered. In general, women who have had mastectomies experience more shoulder problems, such as pain, swelling, and restricted range of motion, post-surgery than those who had a breast conserving surgery (Hayes, Rye, Battistutta, DiSipio, & Newman, 2010; I.-L. Nesvold, Dahl, Løkkevik, Mengshoel, & Fosså, 2008; Rietman et al., 2003; Sugden, Rezvani, Harrison, & Hughes, 1998; Wennman-Larsen, Alexanderson, Olsson, Nilsson, & Petersson, 2013).



**Figure 2.3: Illustration of the affected tissues and surgical area for mastectomy (Canadian Cancer Society, 2015).**

Lymph node biopsies or dissections are performed with both breast conserving surgery and mastectomies to either determine if the cancer has spread to the lymph nodes, or to remove the nodes entirely if there is evidence of cancer. The number of lymph nodes involved with the tumour is directly related to the stage of cancer, as once the cancer has reached the nodes there is an increased likelihood that it will spread to other parts of the body (AJCC, 2009). Sentinel lymph node biopsy (SLNB) and axillary lymph node dissection (ALND) are the two lymph node surgical options. SLNB is the less invasive option; this procedure involves removal of the sentinel node, or the first lymph node in a chain of lymph nodes that receives fluid from the area around the tumour, to determine if it contains cancer (Canadian Cancer Society, 2016). This procedure is for women with early stage breast cancer. If the node contains cancer, most often an ALND will be performed. The ALND procedure removes several lymph nodes in the axilla area (Canadian Cancer Society, 2016). The ALND is a more invasive procedure and is associated with more ensuing symptoms following surgery (Aerts, De Vries, Van Der Steeg, & Roukema, 2011; Crane-Okada, Wascher, Elashoff, & Giuliano, 2008; Hack et al., 1999; Kootstra et al., 2010; Sugden et al., 1998; Wennman-Larsen et al., 2013; Wernicke et al., 2013). However, while SLNB is thought to result in reduced symptoms compared to ALND, previous research has noted incidence of arm morbidities of up to 57.7% two years post-surgery for both types of node removal (Crane-Okada et al., 2008; Kootstra et al., 2010; Verbelen, Gebruers, Eeckhout, Verlinden, & Tjalma, 2014).

Adjuvant treatment, or treatment that is applied after the primary tumour has been removed surgically, is administered if the risk of metastatic disease can be decreased through the use of this treatment. Treatment options consist of radiation therapy, chemotherapy, hormonal therapy, biological therapy, or biophosphonates (Canadian Cancer Society, 2016). The use of these

treatments is situation dependent, but radiation therapy, which uses high energy rays or particles to destroy cancer cells in the applied area, is almost always performed following breast conserving surgery and sometimes after mastectomy (Canadian Cancer Society, 2016). Regardless of type of surgery performed, radiation has also been associated with increased arm dysfunction (Bentzen, Overgaard, & Thames, 1989; Chetty, Jack, Prescott, Tyler, & Rodger, 2000; Hojris, Andersen, Overgaard, & Overgaard, 2000).

### ***2.1.3 Arm morbidities and breast cancer treatment***

Breast cancer survivors may experience a range of upper limb morbidities post-surgery. These morbidities can include symptoms such as restricted range of motion of the shoulder, lymphoedema, decreased strength, pain, the sensation of heaviness, numbness or tightness (Assis, Marx, Magna, & Ferrigno, 2013; Hack et al., 1999; Kuehn et al., 2000), all which can last for several years following surgery. These symptoms are likely due to a number of physical changes resulting from the surgery, such as muscle tissue fibrosis and tissue tightness (Bentzen et al., 1989; S. Johansen, Foss Å, Nesvold, Malinen, & Foss, 2014; Yang et al., 2010), scar tissue formation and diminished tissue healing (Gosselink et al., 2003), as well as nerve dysfunction (Hack et al., 1999; Stubblefield & Keole, 2014). The most commonly assessed arm limitations will be discussed here, followed by a review of the literature assessing post-treatment biomechanics.

#### ***2.1.3.1 Objective and self-reported range of motion***

Restricted mobility, or decreased range of motion, of the shoulder is a common side effect of breast cancer treatment. Breast cancer surgery is an important contributing factor to the restricted range of motion experienced by almost all breast cancer survivors postoperatively (Stubblefield &



Keole, 2014). Up to 85 % of women have reported range of motion restrictions in early post-surgery, and deficits of up to 61° in abduction and flexion have been measured in the first few weeks following treatment (Box, Reul-Hirche, Bullock-Saxton, & Furnival, 2002; Kootstra et al., 2010; Leidenius, Leppänen, Krogerus, & Von Smitten, 2003). Deficits of as little as 10° to 25° compared to the unaffected arm are commonly considered to cause reduced function of the arm (Aerts et al., 2011; S. Johansen et al., 2014; Kootstra et al., 2013; Voogd et al., 2003).

Restricted mobility can also be a long-term symptom of breast cancer treatment. In the first 6-12 months post-surgery, up to 73% of patients have reported some type of shoulder range of motion restrictions in the affected arm (Miedema et al., 2008), while flexion, abduction and external rotation specifically have demonstrated persistent impairments at seven years following surgery, with a decrease in abduction range of motion present in the highest percentage of survivors (Kootstra et al., 2013). In a group of women who had surgery with radiotherapy, 38% reported some mobility impairment nine years post-surgery, but 52% demonstrated impairment when range of motion was objectively measured (Hojris et al., 2000), suggesting that self-reported and objective measured function are incongruent. Over the months and years, the size of the range of motion deficits remain at levels that could impair function. Ranging from 16 to 71 months post-surgery, survivors had range of motion impairments of 30° to 60° in flexion and 65° to 132° in abduction (Bentzen et al., 1989; J. Johansen, Overgaard, Blichert-Toft, & Overgaard, 2000).

While the exact magnitude of range of motion limitation varies, the consistency of reports of problems demonstrates the rising clinical issue of arm impairments as survivorship increases.

Shoulder function impairment and restricted range of motion of breast cancer survivors are also often reported using self-reported paper-and-pen surrogates. One common tool is the Disabilities of the Arm, Hand, and Shoulder (DASH) questionnaire, which is a subjective measure of upper

limb function during activities of daily living and leisure/work activities. Higher DASH scores are associated with both limited range of motion and increased time post-surgery (Assis et al., 2013). Similar to the range of motion results, average DASH scores can slightly increase immediately following surgery, but at 18 months post-treatment, 34% of participants still had a substantial decrease in DASH score (Hayes et al., 2010). Other investigations using different types of self-reported measures have noted that around six to eight months post-surgery, many survivors report that lifting, carrying or reaching worsens their symptoms and decreases their work ability (Kärki, Simonen, Mäkiä, & Selfe, 2005). Another 49% have reported difficulty with recreational activities (Miedema et al., 2008), and 28% have some function problems in their daily life (Bosompra, Ashikaga, Brien, Nelson, & Skelly, 2002) since surgery. Decreases in range of motion and arm function are highly correlated with subjective measurements of pain and reduced working ability; 99% of participants with the highest ranking of shoulder impairment report reduced ability to perform their work tasks (S. Johansen et al., 2014). However, as mentioned above, self-reported issues may not be consistent with measured physical limitations, and their connection to biomechanics and future disability is uncertain.

Physical therapy can have a positive effect on arm mobility. A review of exercise interventions noted that exercise improved mobility at measurements up to 2 years (Chan, Lui, & So, 2010), while physical therapy management has been demonstrated to return average abduction range of motion to normal more quickly than a control group (Box et al., 2002). Physical therapy can also improve self-reported measures of overall function when implemented either 7 or 27 weeks post-surgery (Lauridsen, Tørsleff, Husted, & Erichsen, 2000). Still, it has been noted that physical therapy should be implemented as early as possible to reduce impairments (Johansson, 2005). Although physical therapy appears to decrease the severity and prevalence of post-surgery

mobility impairments, range of motion deficits are clearly still present in some survivors well after physical therapy rehabilitation.

It is important to note that even though some intervention studies find that mean of range of motion for a group of breast cancer survivors can slightly improve over time, a substantial percentage of survivors still display persistent arm impairments. For instance, from measurements at six month to measurements at 18 months, average abduction has been shown to increase by approximately  $7^{\circ}$ , but in that same sample of women 35% still demonstrated a median deficit of  $10^{\circ}$  compared to the unaffected side (Hayes et al., 2010). Similarly, in a study of survivors that were between three months to three years post- mastectomy or -breast conserving therapy, mean abduction and mean flexion improved by  $12^{\circ}$  and  $10^{\circ}$ , respectively, but 31% of that cohort still had some impaired mobility (Devoogdt et al., 2011). It is not yet clear what effect these impairments have on the performance and biomechanics of the shoulder during more functional activities of daily living (ADL's) or work-related tasks, and this will be discussed further in later sections.

#### *2.1.3.2 Lymphoedema*

Lymphoedema is another common arm morbidity following breast cancer surgery.

Lymphoedema is defined as the abnormal collection of excessive tissue proteins, edema, chronic inflammation, and fibrosis (Brennan, 1992). Secondary lymphoedema, often experienced by breast cancer survivors, is caused by the obstruction of the lymphatic system, likely due to the surgical treatment used for breast cancer (Brennan, 1992). Presence of lymphoedema often increases with time; in the first three to six months following treatment, 4% and 7% of women, respectively, reported lymphoedema, with that number increasing to 18% and 13% three and five

years later (Devoogdt et al., 2011; Sagen et al., 2009). Other investigations have reported the prevalence of lymphoedema to range from 19% to 25% at several months to years post-surgery (Assis et al., 2013; Chen et al., 2014; Kootstra et al., 2013; Lacomba, 2010; Voogd et al., 2003). Lymphoedema has been associated with increased feelings of disability and difficulty performing chores or recreational activities (Voogd et al., 2003), as well as increased DASH scores (Dawes, Meterissian, Goldberg, & Mayo, 2008). However, physiotherapy treatment, in the form of manual drainage, compression sleeves, therapeutic exercise and education, does appear to have a positive effect; when comparing an early physiotherapy group to a standard-care control group at one year post surgery, only 7% in the intervention group demonstrated arm swelling, compared to 25% in the control (Lacomba, 2010). Lymphoedema is a complex issue that is not well understood; this treatment side effect may be related to biomechanical alterations or future disability, but more research is needed to determine that connection.

#### *2.1.3.3 Strength*

Upper limb strength is another measure that can be used to define shoulder dysfunction following surgery. However, many studies test grip strength instead of testing the shoulder musculature. Grip strength has demonstrated a fair association with pain in the affected shoulder (Cantarero-Villanueva et al., 2012), and impairments in grip strength of up to 40% over two years post-surgery have been reported (Rietman et al., 2004, 2006; Sagen, Kaaresen, Sandvik, Thune, & Risberg, 2014). Conversely, other investigations have demonstrated no change in hand grip strength post-surgery (Beurskens, van Uden, Strobbe, Oostendorp, & Wobbes, 2007), and thus this may not be a reliable measure of arm impairment or ability to perform functional tasks. More specific shoulder strength deficits and arm weakness can range from 0 to 54% two years post treatment (Assis et al., 2013; Maunsell, Brisson, & Deschênes, 1993; Verbelen et al., 2014),

while the long term effects can affect approximately 20% of survivors up to seven years later (Kootstra et al., 2013). Nevertheless, the influence of reduced strength, and in fact many of the symptoms discussed in this literature review, on functional and work-related task performance is not yet clear.

#### *2.1.3.4 Pain*

Pain of the shoulder, upper limb, and neck is one of the most prevalent and persistent symptoms following breast cancer surgery. Chronic pain is associated with decreased quality of life (Dawes et al., 2008), decreased function or reduced ability to perform daily tasks (Assis et al., 2013; Miedema et al., 2008), and alterations in task performance that could lead to future injuries (Côté, Raymond, Mathieu, Feldman, & Levin, 2005; Galiano-Castillo et al., 2011; Lomond & Côté, 2011; Seaman, Albert, Weldon, Croll, & Callaghan, 2010). Approximately half of breast cancer survivors report some level of pain at some point following surgery (Assis et al., 2013; Levy et al., 2012; Rietman et al., 2006). Specifically, up to 56% of survivors experience pain in the first month of surgery, and 51% still report pain two years post-surgery, according to a review (Verbelen et al., 2014). In a sample of Canadian breast cancer survivors, 55% had pain at three months, and this remained essentially unchanged at 15 months post-surgery (Maunsell et al., 1993). During five year postoperative follow ups, 36% of survivors still reported feelings of pain during rest and activity (Sagen et al., 2009). This is down from 60% at six months, but still remains a large proportion of the population. Finally, 14-22% of women experience self-classified moderate or severe pain (Bosompra et al., 2002; S. Johansen et al., 2014; Miaskowski et al., 2014); higher levels of pain are associated with lowest ranges of motion, lowest functional abilities, and lower wellbeing and quality of life (Bentzen et al., 1989; Miaskowski et al., 2014; Miedema et al., 2008). It is well established that pain is associated with kinematic change; and

thus, the presence of pain is likely to be an important contributor to potential biomechanical alterations during functional task performance.

#### *2.1.3.5 Arm morbidities and secondary rotator cuff disease*

While the symptoms discussed above can independently result in decreased function of the shoulder, they may also predispose breast cancer survivors to future upper limb disorders. Several of these morbidities suggest an increased risk of rotator cuff disease (Stubblefield & Keole, 2014). First, women are most commonly diagnosed with breast cancer in their 50s and 60s, indicating they are already at a higher risk of rotator cuff disease because incidence of rotator cuff tears increases with age (Tempelhof, Rupp, & Seil, 1999; Yamaguchi et al., 2000). Second, tissue tightness and scar tissue formation can be responsible for restricted range of motion ultimately leading to altered postural alignment and shortened chest muscles. These alterations can change both active and passive force generation and distributions surrounding the shoulder, as well as decrease the size of the subacromial space, which is a risk factor for rotator cuff disease (Ebaugh et al., 2011). The presence of lymphoedema can also increase the risk of rotator cuff disease; the increased arm weight associated with lymphoedema can change the scapulohumeral rhythm (Bagg & Forrest, 1988) and result in more stress on the rotator cuff muscles and tendons, potentially leading to overload and tendon tears (Ebaugh et al., 2011; Jang, Kim, Oh, & Kim, 2015). With these specific risk factors in mind, and the demonstrated increase in prevalence of rotator cuff disease in breast cancer survivors from 2.1 % at three months to 7.1% at 12 months post-surgery (Yang et al., 2010), it is likely that biomechanical alterations at the shoulder following surgical treatment are related to pain, disability and future injury. The long-term prevalence of rotator cuff disease in breast cancer survivors is unknown, but the

persistence of morbidities, such as reduced mobility and increased lymphoedema, years after surgery indicate an increased rotator cuff disease frequency.

#### ***2.1.4 Biomechanics and Breast cancer***

Biomechanical evaluation of the shoulder complex following breast cancer treatment is still a relatively new area of research. However, preliminary investigations suggest there are meaningful biomechanical changes that can elucidate current dysfunction and future injury risk.

##### ***2.1.4.1 Kinematics***

Compared to the number of investigations into restricted shoulder range of motion following breast cancer treatment, there has been minimal research into kinematics of the upper limb. Most kinematic measurements of the upper limb have focused on scapula kinematics during arm elevation in various planes and yet the evidence is inconclusive (Borstad & Szucs, 2012; Crosbie et al., 2010; Shamley, Lascrain-Aguirrebeña, Oskrochi, & Srinaganathan, 2012). One investigation reported an increase in internal rotation, or protraction, of the scapula on both sides during scapular plane elevation following surgery, suggesting the unaffected side can also be affected by treatment or by central nervous system changes (Borstad & Szucs, 2012; Doiron, Delacroix, Denninger, & Simoneau, 2010). However, both increases and no changes have also been reported for all scapular degrees of freedom (Borstad & Szucs, 2012; Crosbie et al., 2010; Shamley et al., 2008), and the reported changes in rotation and tilting were relatively small compared to control or pre-measurements, so it is not clear how central these potential alterations are to functional abilities or future injury risk.

Only a few previous investigations have measured three-dimensional upper limb kinematics during functional tasks in breast cancer survivors. During upper limb focused ADL's and basic

work related tasks, scapular posterior tilt range of motion was generally higher in breast cancer survivors than non-cancer controls (Brookham, 2014). Additionally, humeral internal rotation was increased for breast cancer survivors compared to non-cancer controls in all functional tasks, and humeral elevation was higher during ADL tasks for breast cancer survivors (Brookham, 2014). During walking, arms with lymphoedema have reduced arm swing amplitude, drooping shoulder, and centre of pressure was shifted towards the side of the body with the affected arm (Balzarini et al., 2006).

Some of these potential kinematic changes experienced by breast cancer survivors suggest protective mechanisms to prevent specific tissue overload. For instance, increased upward rotation and posterior tilt of the scapula would increase the size of the sub-acromial space, which could decrease shoulder impingement syndrome symptoms (Kibler & McMullen, 2003; Ludewig & Cook, 2000). However, other kinematic alterations potentially increase injury risk. In particular, the increased protraction of the scapula and increased internal rotation of the humerus would actually decrease the size of the subacromial space, which would in turn increase the risk of impingement (Braman, Engel, LaPrade, & Ludewig, 2009; Ludewig & Cook, 2000; Solem-Bertoft, Thuomas, & Westerberg, 1993). The magnitude of the protraction of the scapula changes in preliminary studies appears to be larger than the magnitudes of the upward rotation and posterior tilt alterations, indicating the overall changes could be increasing injury risk and symptoms. The reduced ability to use full arm elevation range of motion could also lead to kinematic changes and increased loading at adjacent segments, such as the torso (Côté et al., 2005; Lomond & Côté, 2011), depending on specific tasks requirements.



#### *2.1.4.2 Electromyography*

Muscle activation strategy is also affected by breast cancer treatments. In one study, during arm elevation, the posterior deltoid and supraspinatus muscles had higher activity levels compared to controls (Brookham, 2014), while the pectoralis major (sternal head), infraspinatus, upper trapezius, serratus anterior, and rhomboids had decreased activity (Brookham, Cudlip, & Dickerson, 2018b; Shamley et al., 2007). During functional upper limb tasks, increases were present in the posterior deltoid, upper trapezius, supraspinatus, and sternocleidomastoid, while pectoralis major and infraspinatus had decreased activity (Brookham, 2014; Galiano-Castillo et al., 2011). Decreased muscle activity, such as the reduced EMG seen in the pectoralis major muscle, may reflect weakness in those muscles (Shamley et al., 2007). Overall total relative muscle effort was increased on the affected side during work tasks, reflecting increased muscle work that could speed fatigue and injury risk (Brookham, 2014). However, these muscle strategy changes have not been explicitly connected to functional decrements or injury risk, so the implications for rehabilitation and long term function are yet to be determined.

#### *2.1.4.3 Future injury risk*

Biomechanical changes are important to monitor because several of the alterations preliminarily found in breast cancer survivors are similar to the changes observed in other shoulder impairment groups. Increased protraction of the scapula and internal rotation of the humerus, both of which have been documented in breast cancer survivor groups, are kinematic adaptations of persons with either impingement or glenohumeral instability (Ludewig & Reynolds, 2009). Increased internal rotation and anterior tilting of the scapula frequently co-exist with both shoulder impingement and shortened pectoralis muscles, which is an observed side effect of

breast cancer surgery (Phadke, Camargo, & Ludewig, 2009). Similarly, increased upper trapezius and deltoid activity, along with decreased activity of the serratus anterior and rotator cuff muscles are muscle strategy alterations displayed by both breast cancer survivors and shoulder impingement patients (Phadke et al., 2009), supporting the hypothesis that breast cancer survivors are predisposed to rotator cuff disease.

Kinematic alterations and reductions in range of motion can also cause compensations at adjacent joints. Injured individuals often reduce the variability of movement at the affected structures, resulting in increased exposure at those structures and potential change in motion at other joints (Mathiassen, Möller, & Forsman, 2003). For instance, shoulder-injured groups often decrease the range of motion at the shoulder or elbow while simultaneously increasing centre of mass of trunk motion (Lomond & Côté, 2011; McClure, Michener, & Karduna, 2006; Roy, Moffet, & McFadyen, 2008). Therefore, the reduced ability of breast cancer survivors to use their shoulders may lead to undesired compensations at other areas of the kinetic chain in order to perform defined tasks. Improved understanding of how kinematics are altered by breast cancer surgery and how those alterations relate to kinematic changes in other pathological groups will help to direct physical therapy treatment, shoulder rehabilitation, and return-to-work planning.

#### ***2.1.4 Correlation with Quality of Life***

Breast cancer surgery and the subsequent physical symptoms also influence overall perception of quality of life and mental health. Pain, lymphoedema and restricted range of motion are most significantly associated with decreased quality of life (Aerts et al., 2011; Assis et al., 2013; I. L. Nesvold, Reinertsen, Fossa, & Dahl, 2011). Alterations of scapula kinematics are also related to overall decreases of quality of life and other subjective measures (Borstad & Szucs, 2012).

Interestingly, quality of life may only be decreased in breast cancer survivors under 65 (Pinto et

al., 2013), indicating younger women are most affected by the physical limitations following surgery, possibly because they have higher physical work and home demands. When there are difficulties performing such daily tasks, this can lead to a higher prevalence of mental health issues such as anxiety or depression (Caban et al., 2006; Hayes et al., 2010). As such, return-to-work is an important parameter to consider for quality of life, as working has known positive effects on mental health and quality of life (Anderson & Armstead, 1995). However, neither capacity nor movement strategies during work-related tasks of breast cancer survivors has been investigated. Better definition of these parameters would lead to better management of symptoms and appropriate, healthy return-to-work, which would potentially lead to improved quality of life and function in all aspects of life.

#### ***2.1.5 Return-to-work in breast cancer survivors***

Status as a cancer survivor interacts with employment rates and other work factors. An investigation of several types of cancer noted that only 40% of patients continue to work during treatment (Short, Vasey, & Tunceli, 2005). Following treatment, cancer survivors are more likely to be unemployed than healthy control participants (de Boer, Taskila, Ojajarvi, van Dijk, & Verbeek, 2009), and only approximately two-thirds of cancer survivors return to their jobs (de Boer et al., 2009; Spelten, Sprangers, & Verbeek, 2002). In addition, many cancer survivors who do return to employment report work ability limitations in the years following diagnosis (Short et al., 2005). Reduced hours, role changes, or job changes are also common for survivors that return to work after treatment, and these changes are often considered related to cancer (Steiner, Cavender, Main, & Bradley, 2004). While returning to work is important for cancer survivors' physical and mental health, it is clear that the majority of survivors experience problems that interfere with returning to employment.

Breast cancer survivors have a relatively high return-to-work rate, compared to return-to-work rates of all types of cancer. However, the results of a meta-analysis suggest that breast cancer survivors are still more likely to be unemployed than non-cancer controls up to 9 years following treatment (de Boer et al., 2009). In the first several weeks following surgery, up to 85% of women are absent from work (Drolet, Maunsell, Mondor, et al., 2005) and are supplementing their income with sick leave, long term disability, or employment insurance (Canadian Breast Cancer Network, 2010). Sick leave in the first three months after surgery is associated with lower age, strenuous work posture and physical symptoms (Wennman-Larsen et al., 2013), suggesting younger women in more physically intensive jobs are experiencing the highest economic effects of cancer. In Canada, 64% of women who received breast cancer treatment in the last five years had returned to work, but full time work reduced from 61% at time of diagnosis to 45% up to five years later (Canadian Breast Cancer Network, 2010). The long term return-to-work rates following breast cancer treatment range from 33% to 85% following treatment (Ahn et al., 2009; Drolet, Maunsell, Brisson, et al., 2005; Hoving, Broekhuizen, & Frings-Dresen, 2009), but return-to-work rates of 75 to 85% are reported following some type of rehabilitation intervention (Hoving et al., 2009). Targeted rehabilitation informed by results of functional, return-to-work task performance could help to raise both of these values. Due to the importance of return-to-work to overall health and quality of life, there is a need to address and improve safe work ability and subsequent return-to-work rates for breast cancer survivors. Better understanding of functional capacity and task performance of breast cancer survivors is the first step to improved assessment and treatment of return-to-work ability.

Breast cancer survivors experience many physical symptoms following treatment that could affect their ability to perform their work related tasks. These physical alterations, such as

decreased range of motion, fibrosis, or lymphoedema, are potentially associated with kinematic alterations that can lead to subsequent work related injuries and more time off work that would then add to the financial burden already experienced by cancer survivors (Canadian Breast Cancer Network, 2010). Identifying pathological biomechanics displayed by breast cancer survivors during work-related functional tasks can help reveal how these mechanics can be treated to both improve the return-to-work likelihood for breast cancer survivors and prevent future time-loss injuries.

## **2.3 Overview of modelling methods and approach**

Musculoskeletal (MSK) modelling provides a framework to estimate internal loads on the human musculoskeletal system in order to understand how different scenarios can influence localized tissue demands. MSK modelling provides insight into muscle function beyond what can be empirically measured. This knowledge is useful as context for effective injury prevention and treatment of MSK disorders.

### ***2.3.1 Modelling pathological shoulders***

Biomechanical models of the shoulder provide estimates of internal exposures caused by external demands. This information is often used for four main purposes: (1) to define and understand fundamental shoulder biomechanics; (2) to determine the effect of different tasks on shoulder function; (3) to determine the effect of structure differences on shoulder function; or (4) to determine the effect of morphological differences on shoulder function (Bolsterlee, Veeger, & Chadwick, 2013). For a pathological population, the goal of modelling is most often to examine how structural differences, caused by injury or disorder, affect function. For instance, MSK modelling has been used to determine how joint mechanics and muscle function change following rotator cuff tears (Campbell et al., 2014; Lemieux et al., 2012). Using both cadaver and computer simulated models, increased acromio-humeral pressures after rotator cuff tears were confirmed. Modelling demonstrated that increased pectoralis major and latissimus dorsi muscle activation can resist humeral head migration following a tear, suggesting that rehabilitation for rotator cuff tears should include further strengthening or training of these muscles (Campbell et al., 2014; Lemieux et al., 2012).

Following breast cancer surgery, the force capability of the pectoralis major muscle is comprised. Pectoralis muscle size is reduced after treatment (Shamley et al., 2007) and the affected side has demonstrated decreases in torque after curative surgery and immediate reconstruction (de Haan, Toor, Hage, Veeger, & Woerdeman, 2007). The reduction in force capability is a result of damage to the pectoralis muscle from the treatment. This damage can be because of resection or other harm to the fascia from surgery (Dalberg et al., 2010; Muscolino, Leo, Sacchini, Bedini, & Luini, 1988). The nerves that innervate the pectoralis muscle are also often damaged in curative and reconstructive surgery (Muscolino et al., 1988; Wedgwood & Benson, 1992). Moreover, the anterior wall muscles can experience vascular changes or scarring from radiation treatment (Soulen et al., 1997). There is need to investigate how shoulder function is affected by the damage and subsequent reduced capability of the pectoralis major muscle. Determining how muscle force estimates are affected by these altered structures, and potentially altered kinematics, can help to detect previously unknown force deficits or uncharacteristically high force levels that could identify dysfunction and future injury potential.

### ***2.3.2 Biomechanical modelling fundamentals***

There are three main steps involved in calculating muscle force estimates: (1) measure the external loads and define segment postures, (2) determine and define the tissue and joint properties, and (3) calculate the internal forces. The simplest way to estimate internal forces is to use a single muscle equivalent model. This method assumes there is only one muscle, or one group of muscles, with one line of action resisting the external moment. However, this approach does not accurately reflect the human musculoskeletal system, as there are several agonists and antagonists working around each joint to produce the desired movement or moment (Winter, 2009). Additionally, there are several different combinations of muscle actions that can produce

the same movement or force, leading to a redundancy or indeterminacy problem (An, Kwak, Chao, & Morrey, 1984). In order to address these factors, there is a need to reduce the problem.

There are a variety of different types of biomechanical models that can be used to answer a range of questions, and they most often use an inverse dynamic solution, meaning they predict muscles forces that equal the external moments. Optimization is one method to address the indeterminacy of muscle strategies. When optimizing, the goal is to either minimize or maximize some cost function (Crowninshield & Brand, 1981). For instance, the objective function of most models is to minimize physiological cost while still being bound by several constraints to improve physiological accuracy, such as equilibrium, stability, or cross sectional area and capacity of the muscles (Challis, 1997; Crowninshield & Brand, 1981; Dickerson, Chaffin, & Hughes, 2007; Dul, Johnson, Shiavi, & Townsend, 1984).

This thesis used a previously developed musculoskeletal model, called the Shoulder Loading Analysis Module (SLAM) (Dickerson et al., 2007). This model uses an inverse dynamics approach and requires external loads or forces and certain segment parameters be measured. This information, along with measured kinematic data, are inputs into the model. The cost function is to minimize the sum of the cubed muscle stresses and the model includes translational and rotational multi-joint equilibrium and stability constraints (Dickerson et al., 2007). This model has previously been used on a breast cancer survivor population; it was determined that reducing the force capacity of the pectoralis major (sternal and clavicular heads) resulted in general agreement of muscle force predictions (in the form of % of capacity) compared to EMG measurements for static external rotation exertions (Chopp-Hurley, Brookham, & Dickerson, 2016). The use of this model in the current set of studies will further test its ability to model the muscle dysfunction in breast cancer survivors and continue to work towards understanding the



adaptive muscle strategies used by this group. Any differences in kinematics can be directly tied to differences in muscle force predictions, providing unprecedented insight into breast cancer survivor shoulder function.

Defining kinematic and kinetic outcomes during functional tasks performance in breast cancer survivors will enhance understanding of shoulder dysfunction, however, there is still a need to translate the information to clinicians.

## **2.4 Clinical evaluation of the shoulder**

Clinicians must be able to identify and interpret kinematic alterations and movement strategy improvements in a clinical setting when evaluating any joint or injury. With this in mind, the following section reviews common methods of assessing the shoulder in a clinical setting.

### ***2.4.1 Thoracohumeral Motion Clinical Assessment***

Clinical evaluation of the humerus almost exclusively involves assessment of thoracohumeral range of motion. Maximum arm elevation in abduction, flexion, and scaption (scapular plane elevation), humeral extension, and humeral internal and external rotation are often evaluated using observation or simple measurement tools such as goniometers and inclinometers (Hayes, Battistutta, & Newman, 2005). Assessment of range of motion is a relatively easy and repeatable evaluation method that provides some understanding of potential abilities or dysfunction, although accuracy and reliability depend on the measurement method used (Holm et al., 2000; Watkins, Riddle, & Lamb, 1991; Williams & Callaghan, 1990). There is some question regarding clinicians' ability to determine the presence of arm impairment during elevation in different planes (Hickey, Milosavljevic, Bell, & Milburn, 2007; Lang & Milosavljevic, 2019), and it is not completely clear how range of motion changes relate to daily activities or functional task performance.

Evaluation of thoracohumeral motion during more complex, functional tasks does take place in return-to-work assessments, most often through observation. However, observation guidelines for upper limb focused Functional Capacity Evaluation (FCE) tasks are limited and vague (Trippolini et al., 2014), so clinicians have inadequate guidance for determining potentially harmful movements or kinematics that are characteristic of arm impairment. This author's

previous work attempted to improve the understanding of motion during FCE tasks by creating a normative kinematic dataset from a young, healthy sample that can be used for comparison of a patient's kinematics (Lang & Dickerson, 2017b). However, it has not yet been determined how different pathological shoulder groups may perform these standard return-to-work evaluation tasks.

#### ***2.4.2 Scapular Motion Clinical Assessment***

A variety of measurement and assessment methods exist that attempt to aid clinicians with evaluation of scapular motion, although this is often difficult to do in a clinical setting. Most methods focus on identifying 'scapular dyskinesis', or altered scapular motion or positioning, as there is evidence that dyskinesis is related to shoulder pain or impairment (Kibler et al., 2013). Nearly all tests involve assessment during arm elevation. The most basic tests involve measuring the distance between pre-determined anatomical landmarks during a relaxed position and then again in retraction to determine potential pectoralis shortness, which is associated with poor scapular posture and increased scapular winging (da Costa et al., 2010; Ludewig et al., 2009; Nijs, Roussel, Struyf, Mottram, & Meeusen, 2007; Nijs, Roussel, Vermeulen, & Souvereyns, 2005; Struyf et al., 2012). Another test, the lateral scapula slide test, is based on this same concept (Kibler, 1998; Odom, Taylor, Hurd, & Denegar, 2001; Struyf et al., 2012). Scapular upward rotation position during arm elevation is another common measure of dyskinesis. This method utilizes inclinometers affixed to the humerus and the scapula; the patient is then instructed to elevate their arm to specific levels, as determined by the humerus inclinometer, and then the level of upward rotation is read from the second inclinometer (L. J. Johnson & Miller, 2001; Struyf et al., 2012; Watson, Balster, Finch, & Dalziel, 2005). This test provides insight into scapulohumeral rhythm (Bagg & Forrest, 1988). Finally, winging of the scapula during

static pressing is another common outcome of clinical assessment. Scapula winging has been defined as when the medial border and/or inferior angle of the scapula are posteriorly displaced away from the posterior thorax (McClure, Tate, Kareha, Irwin, & Zlupko, 2009) and indicates weakness or inefficient activation of the serratus anterior muscle (Nijs et al., 2007). This is often tested by observing medial border prominence during forward flexion or performance of a wall push (Khadilkar, Chaudhari, Soni, & Bhutada, 2015; McFarland, Garzon-Muvdi, Jia, Desai, & Petersen, 2010).

Scapular dyskinesis during dynamic movement is most often evaluated visually. The 4-type method for categorizing scapular dyskinesis involves observing the scapular border position at rest and during elevation (Kibler et al., 2002). Three types of scapular movement patterns indicate asymmetries and one type describes symmetric motion: a Type I pattern displays excessive prominence of the inferior angle of the scapula, Type II involves prominence of the entire medial scapular border, Type III demonstrates excessive superior migration of the superior scapular border, while normal, symmetrical motion is designated Type IV (Kibler et al., 2002; Uhl, Kibler, Gecewich, & Tripp, 2009). A simplification of this method, called the yes/no method, collapses Types I-III into one category, ‘yes’, if any type of dyskinesis was observed, and Type IV is relabeled ‘no’ to represent normal motion (Uhl et al., 2009).

These scapular evaluations all occur during static and dynamic basic arm elevation. This is the prevailing method for assessment, and many of the tests explained above (the scapular positioning measurements, upward rotation evaluation, the LSST, and the 4-type and yes/no observation methods) demonstrate good agreement and reliability (Kibler et al., 2002; Nijs et al., 2007, 2005; Odom et al., 2001; Uhl et al., 2009; Watson et al., 2005). Both the measurement and external validity of these tests are not well established, bringing into question the usefulness of

these assessments during a clinical evaluation (Nijs et al., 2007). Functional task evaluation is more complex, but considering the lack of consensus about the utility of these evaluation methods, exploration of scapular positioning during functional tasks is warranted.

## **2.5 Literature Review Conclusion**

It is well established that shoulder dysfunction is prevalent in breast cancer survivors. Arm limitations following breast cancer treatment range from decreases in shoulder range of motion and shoulder strength to increases in arm swelling and pain. These arm morbidities are also associated with other upper limb injuries, particularly rotator cuff disease, but the link between the treatment side effects and further injury is not yet established. There is some evidence to suggest that shoulder biomechanics are altered following treatment, potentially with similar alterations as individuals with rotator cuff disorder, but there is minimal information regarding shoulder biomechanics in functional tasks. Identifying common biomechanical alterations in functional tasks that are performed regularly at work or at home will highlight movement strategies that can lead to further injury and disability if not appropriately addressed. Further, estimating muscle forces for all muscles surrounding the shoulder will provide insight into why these biomechanical alterations are present (i.e. identifying muscle weaknesses). Taken together, these kinematic data and muscle force estimates can guide rehabilitation and return-to-work programs. However, for this information to be used by clinicians, they have to be able to identify or observe the altered biomechanics at the shoulder. Shoulder and scapular movement is most often evaluated during arm elevation, but it is not clear if this is a sufficient method to determine kinematic alterations during functional tasks. Characterizing the relationship between kinematics during arm elevation and functional tasks will address this disconnect between daily task performance and clinical evaluation.

The first step to achieving these objectives is to confirm the utility of the proposed method for scapular motion measurement. The AMC was used to track the motion of the scapula. This strategy has been used in previous research, but most investigations have had young, active,

impairment-free participants (Karduna et al., 2001; Maclean et al., 2014; van Andel et al., 2009).

To enhance confidence in kinematic, kinetic, and clinical results, the AMC accuracy was assessed in the current sample. The first manuscript of this thesis is comprised of this investigation.

## **CHAPTER 3: THE UTILITY OF THE ACROMION MARKER CLUSTER (AMC) IN A CLINICAL POPULATION**

Angelica E. Lang<sup>1</sup>, Soo Y. Kim<sup>2</sup>, Stephan Milosavljevic<sup>2</sup>, & Clark R. Dickerson<sup>3</sup>

<sup>1</sup> Department of Health Sciences, College of Medicine, University of Saskatchewan, Canada

<sup>2</sup> School of Rehabilitation Science, College of Medicine, University of Saskatchewan, Canada

<sup>3</sup> Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, Canada

### **Contribution:**

Angelica Lang was a primary contributor to the study conception and design. She led and completed all participant recruitment, data collection sessions, and data analysis. She was also the primary author of the manuscript.

### **Publishing status:**

This article was published in the Journal of Electromyography and Kinesiology, International Shoulder Group Special Edition:

**Lang, A.E.**, Kim, S.Y., Milosavljevic, S.M., & Dickerson, C.R. (2019). The utility of the acromion marker cluster (AMC) in a clinical population. *Journal of Electromyography and Kinesiology (International Shoulder Group Special Issue)*, in press.



### 3.1 Abstract

**Introduction:** The acromion marker cluster (AMC) is a non-invasive scapular motion tracking method. However, it lacks testing in clinical populations, where unique challenges may be present. This investigation resolved the utility of the AMC approach in a compromised clinical population.

**Methods:** The upper body of breast cancer survivors and controls were tracked via motion capture and scapular landmarks palpated and recorded using a digitizer at static neutral to maximum elevation postures. The AMC tracked the scapula during dynamic maximum arm abduction. Both single (SC) and double calibration (DC) methods were applied to calculate scapular angles. The influences of calibration method, elevation, and group on mean and absolute error with two-way fixed ANOVAs with interactions ( $p < 0.05$ ). Root mean square errors (RMSE) were calculated and compared.

**Results:** DC improved AMC estimation of palpated scapular orientation over SC, especially at higher arm elevations; RMSE averaged  $11^\circ$  higher for SC than DC at maximum elevation, but the methods were only  $2.2^\circ$  different at  $90^\circ$  elevation. DC of the AMC yielded mean error values of  $\sim 5\text{-}10^\circ$ . These approximate errors reported for AMC with young, lean adults.

**Conclusions:** The AMC with DC is a non-invasive method with acceptable error for measuring scapular motion of breast cancer survivors and age-matched controls.

## 3.2 Introduction

Scapulothoracic motion is critical for shoulder function. The scapula, clavicle, and thorax form the shoulder girdle and together with the humerus create a closed kinematic chain, in which bony orientations depend on one another. This relationship is referred to as the “shoulder rhythm”.

Often only the two-dimensional (2-D) aspect of the shoulder rhythm, the ratio of humeral elevation to scapular upward rotation, is considered when assessing shoulder motion in a clinical setting (Bagg & Forrest, 1988; M. P. Johnson, McClure, & Karduna, 2001). While 2-D shoulder rhythm can be a useful clinical measure, true shoulder motion is more complex and incorporates three-dimensional (3-D) aspects that still need to be investigated further, especially in non-typical groups.

Alterations in scapulothoracic motion are associated with upper limb pathologies. Breast cancer survivors often experience upper limb dysfunction, and possible scapulothoracic kinematic alterations. Upper limb limitations in the form of reduced shoulder range of motion, reduced strength, and increased pain, among others, are well documented in breast cancer survivors (Assis et al., 2013; Hack et al., 1999; Lang, Murphy, Dickerson, Stavness, & Kim, n.d.).

However, scapulothoracic motion changes and their implications have not been conclusively determined. Previous investigations have reported changes in all three scapulothoracic degrees of freedom; post-treatment shoulders have demonstrated increased protraction (Borstad & Szucs, 2012), increased upward rotation (Crosbie et al., 2010), or increased posterior tilt (Shamley et al., 2008), with differences ranging from 5-15°. Overall, description of scapulothoracic motion changes in breast cancer survivors are inconclusive, which may be a function of varying methods and procedures. Determining the implications of motion capture measurement choices for

describing scapulothoracic kinematics in breast cancer survivors could help to standardize methods and improve interpretation of results.

Accurately measuring scapulothoracic motion for both typical and pathological human movement has presented a challenge for biomechanical researchers. Pins surgically placed in bones (Braman et al., 2009; Ludewig et al., 2009; McClure, Michener, Sennett, & Karduna, 2001) are the gold standard for motion capture, but this strategy is not feasible for most data collections, particularly with a clinical population. Various non-invasive scapular tracking methods exist to address the need for scapular kinematics for movement evaluation and inputs into MSK models, including the scapular locator (Barnett, Duncan, & Johnson, 1999; Meskers, Vermeulen, De Groot, Van Der Helm, & Rozing, 1998) and the acromion marker cluster (AMC) (Karduna et al., 2001; Maclean et al., 2014; van Andel et al., 2009; Warner, Chappell, & Stokes, 2012). While the locator is currently considered to be the most accurate non-invasive method (Cutti & Veeger, 2009), the locator can only provide information about static scapular orientations, as it needs to be repositioned with every movement, similar to the palpation method (Maclean et al., 2014). The AMC is placed on the flat part of the acromion and has the capability to track dynamic scapular motion (Maclean et al., 2014). Up to 120° of arm elevation, the AMC demonstrated good agreement with bone pins (Karduna et al., 2001), but past this level, errors can increase to up to 20°. Improved calibration methods may increase AMC accuracy at higher levels of arm elevation (Brochard, Lempereur, & Rémy-Néris, 2011). However, most examinations of validity have only recruited young and healthy volunteers (Karduna et al., 2001; Maclean et al., 2014; Meskers, van de Sande, & de Groot, 2007; Rapp, Richardson, Russo, Rose, & Richards, 2017; van Andel et al., 2009; Warner et al., 2012). The AMC has not been tested with clinical populations, who can present further challenges with data collection, due to

movement restrictions, comfort levels, and different body compositions compared to a young, healthy group.

The objective of this study was to test the accuracy of the AMC approach for scapula motion tracking and to determine its ability to track scapular motion in a clinical population. A secondary aim was to compare two calibration methods of the AMC to determine a preferred approach for AMC use.

### **3.3 Methods**

A cross sectional lab-based comparison of scapular angles calculated from static palpations and dynamic tracking with AMC for two groups was used to assess the ability of the AMC to track scapular motion.

#### ***3.3.1 Participants***

Fifty participants contributed to the study: 25 breast cancer survivors and 25 age group-matched controls (Table 2.1). All participants were females between the ages of 35 and 65. Inclusion criteria required breast cancer survivors to have had either unilateral or bilateral mastectomy at least six months prior to participation. Controls were required to have no known current upper limb impairments. Upon arrival, participants were evaluated with three common impingement tests: Neers' sign, Hawkins-Kennedy, and empty can (Calis, 2000; Moen, de Vos, Ellenbecker, & Weir, 2010). A positive result on any test warranted exclusion from the control group. The study protocol was approved by the University of Saskatchewan Research Ethics Board and all participants provided written informed consent.

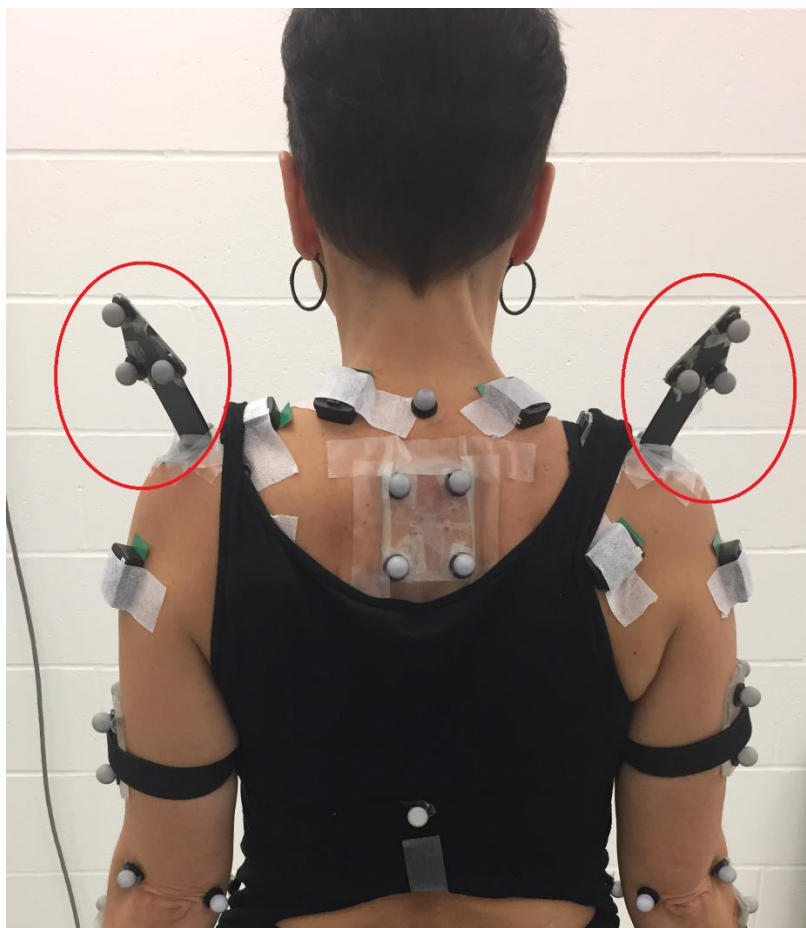
**Table 3.1: Participant demographics. Disability score (QuickDASH) was the only significant difference between the groups.**

<b>Measure</b>	<b>Control (n = 25) Mean (SD)</b>	<b>Breast cancer survivors (n = 25) Mean (SD)</b>
<b>Age</b>	51.6 (6.9)	54.1 (5.2)
<b>Weight (kg)</b>	68.7 (11.8)	72.4 (15.3)
<b>Height (m)</b>	1.62 (0.08)	1.61 (0.06)
<b>BMI (kg/m<sup>2</sup>)</b>	26.2 (4.8)	27.4 (6.5)
<b>QuickDASH (/100)</b>	4.7 (6.3)*	16.7 (10.6)*
<b>Time since mastectomy (months)</b>	n/a	56.8 (4.7)

\*denotes significant difference between the groups based on t-test ( $p < .05$ ).

### **3.3.2 Instrumentation**

Position of the thorax, upper arms, and scapulae were tracked with ten Vicon MX20 optoelectronic cameras. Individual markers were affixed to the skin at thorax and humeral anatomical points per International Society of Biomechanics recommendations (G. Wu et al., 2005) (Table 3.2) and rigid clusters for additional tracking markers were placed on the thorax and humeri (Figure 3.1). Scapulae anatomical points were digitized during static positions and movement of the scapula was tracked with the AMC during dynamic motions (Maclean et al., 2014). Data were sampled at 50 Hz.



**Figure 3.1: Marker set up of the upper body from a posterior view. Circles indicate the location of the AMC.**

**Table 3.2: Landmark locations of anatomical markers**

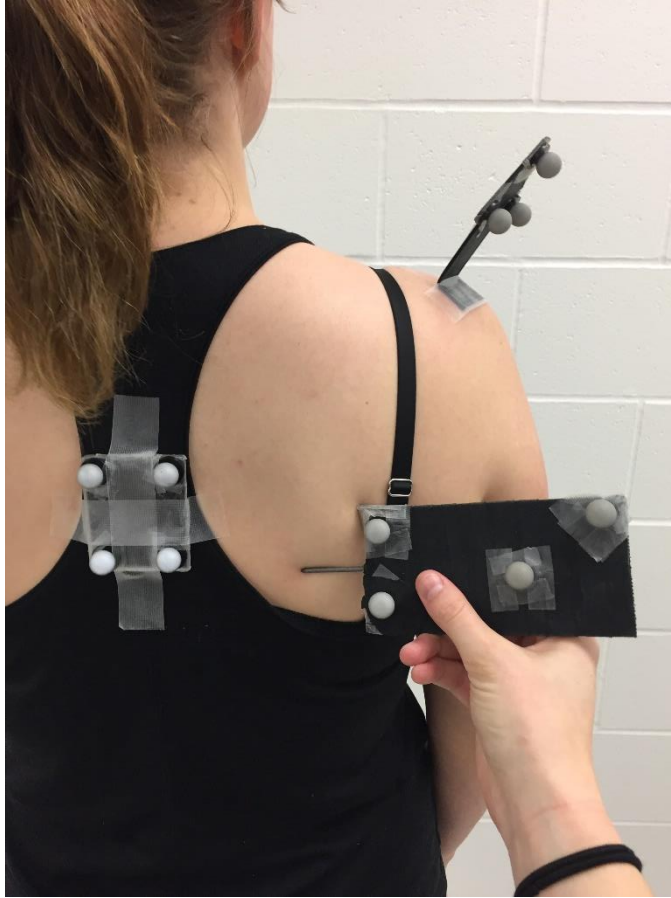
Marker	Description
SS	Suprasternal notch
C7	Spinous process of the 7 <sup>th</sup> cervical vertebra
XP	Xiphoid Process
T8	Spinous process of the 8 <sup>th</sup> thoracic vertebra
AA*§	Acromial Angle (most latero-dorsal point of the scapula)
TS*§	Trigonum Spinae Scapulae (root of scapular spine)
IA*§	Inferior angle of the scapula
ME*	Medial epicondyle of the humerus
LE*	Lateral epicondyle of the humerus

**\*indicates bilateral placement**

**§indicates location of digitized anatomical points on the scapulae**

### **3.3.3 Procedure**

Calibration of the thorax and humeri was performed immediately after equipment set up, followed by static scapular palpations. Participants were asked to stand comfortably while the scapular resting position was palpated and digitized on both sides (Figure 3.2). Scapula orientation at 90° of arm elevation in the frontal plane, as measured by a goniometer, and at maximum arm elevation were digitized for all participants while standing with the elbow extended, alternating between the right and left side. To expand the dataset while also managing time and resources, for the last 12 breast cancer survivor participants scapular orientation at 30°, 60°, and 120° of humeral elevation were also digitized for both sides. Static scapular angles were calculated for each elevation level using digitized points, while only digitized points at rest and maximum were used for calculation of angles in dynamic measurements. Humeral elevation levels were chosen to correspond to previous investigations of scapular motion tracking (Karduna et al., 2001; van Andel et al., 2009).



**Figure 3.2: Digitization of the inferior angle of the scapula at neutral.**

Dynamic arm elevations were performed in the frontal plane while standing. Arm motion was guided by an upright pole to keep the arm in the correct plane. Participants were instructed to raise their arm as high as they could and then lower to the starting position at a comfortable pace, an approximate average of four seconds. The elbow was extended and palm faced forward throughout the movement.

### **3.3.4 Analysis**

Motion capture data were used to calculate scapular and humeral angles. All data were filtered with a low-pass zero-lag fourth order Butterworth filter with a cut-off frequency of 6 Hz.

Humeral elevation was defined as the angle between the long axis of the humerus and long axis



of the thorax to ensure that elevation angle calculations were not affected by rotation sequence, while Euler angles using the YXZ rotation sequence (G. Wu et al., 2005) were used to describe scapulothoracic rotations. For static palpations, scapular orientation was calculated at each position using the digitized points. Humeral elevation was also calculated at each static position and dynamic trials were resampled based on these values: scapular orientation from the frames in the dynamic trials in which humeral elevation angle was within  $\pm 2$  degrees of humeral elevation in the static positions were selected for comparison. Elevation levels are referred to as goniometer measurements ( $30^\circ$ ,  $60^\circ$ ,  $90^\circ$ ,  $120^\circ$ ) for parsimony, but actual humeral elevation levels are noted in the results (Table 2). Two calibration methods were used to evaluate scapular angle in dynamic trials: single calibration (SC), using only the palpated scapula landmarks in relation to the AMC while standing in neutral, and double calibration (DC), which used scapula orientation in relation to the AMC at neutral and maximum arm elevation (Brochard et al., 2011; Rapp et al., 2017). The two positions palpated in the DC method were considered the maximum and minimum values, and the AMC to scapula transformation matrices were then interpolated between the two points based on humerothoracic elevation (Rapp et al., 2017) to calculate scapular angles throughout dynamic motions.

Error of the AMC was calculated as scapular angle during dynamic trials minus scapular angle at palpation, meaning a positive difference indicates an over estimation by the AMC. Eighty-four out of the 2,112 angles were excluded due to motion capture error or because humeral elevation was not in the  $\pm 2^\circ$  range of humeral elevation. Mean error, absolute mean error, and root-mean-square error (RMSE) were then calculated for both methods.

Two separate analyses were performed due to the subset of participants that were tested at all elevation angles. A three-way ANOVA with interactions was used to test the influence of

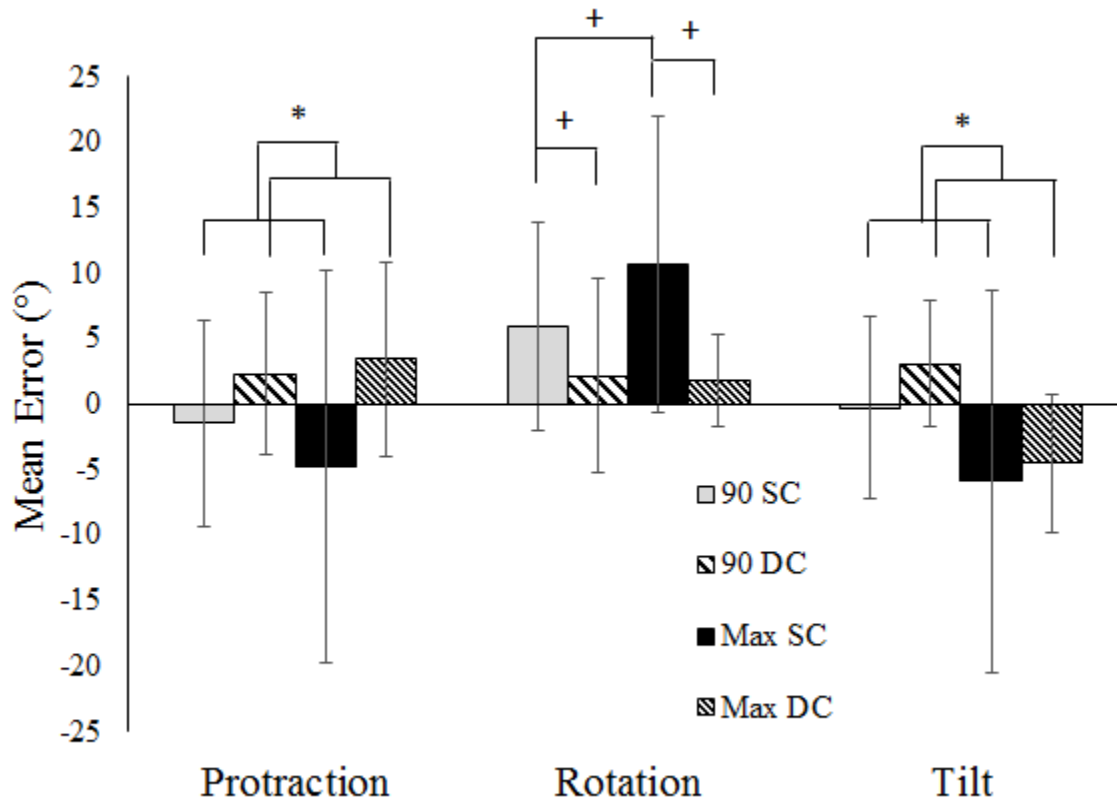
calibration (single vs double), elevation (90°, maximum), and group (breast cancer survivors vs controls) on mean and absolute error of all 50 participants. For the subset of 12 participants that were tested at all five elevation levels, all of which were breast cancer survivors, a two-way ANOVA with interactions was used to test the effects of calibration and elevation (30°, 60°, 90°, 120°, maximum) on errors. Post-hoc Tukey HSD was used to confirm significant differences at the  $p \leq 0.05$  level.

### **3.4 Results**

#### ***3.4.1 Calibration and elevation interaction***

Mean upward rotation angle error was affected by the interaction of calibration method and elevation. This interaction is best shown by the data from all participants at 90° and maximum elevation; errors at 90° and maximum elevation levels were only different when using SC, while errors between calibration methods differed at each elevation level ( $p = .028$ ) (Figure 3.3).

Calibration method and elevation angle also interacted to influence absolute errors at all degrees of freedom ( $p < .001$ ). Absolute errors were different between calibration methods at the higher arm elevations (Figure 3.4).

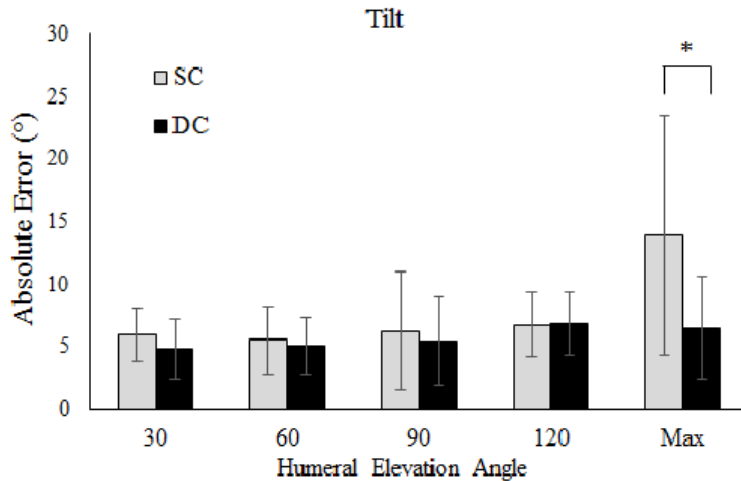
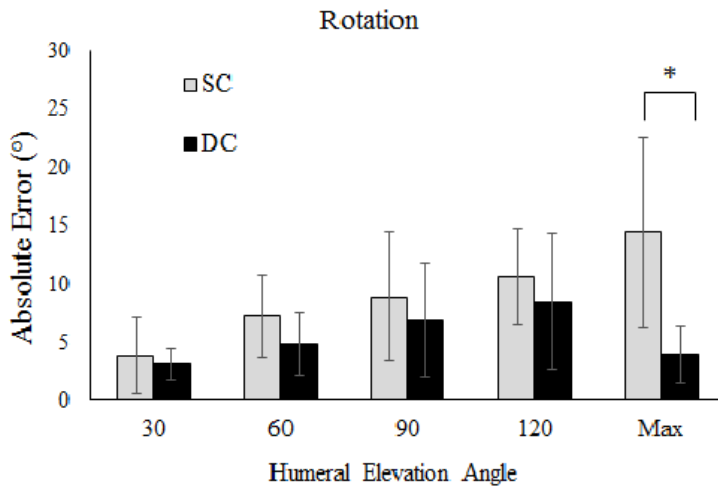
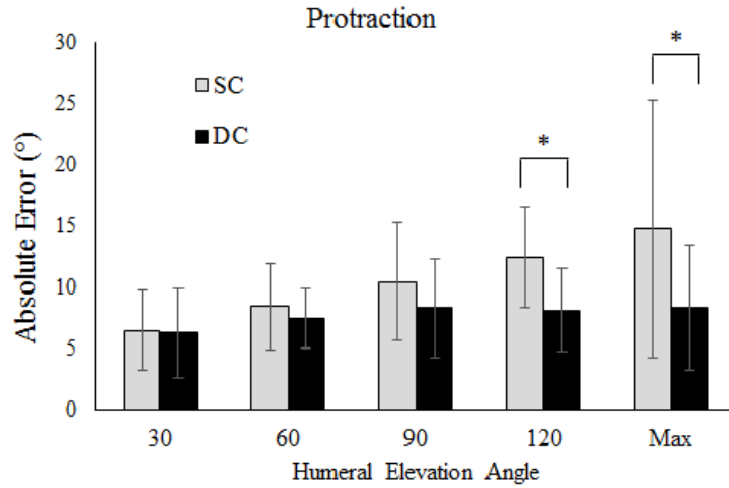


**Figure 3.3: Mean error at 90° and maximum arm elevation for all participants.**

**+ denotes significant interaction of calibration method and elevation angle**

**\* denotes significant main effect of calibration method.**

There was also a main effect of calibration method for all angles ( $p < .001$ ); mean errors were larger using SC, with the largest error of  $10.7^\circ$  occurring for upward rotation at maximum elevation when using SC (Figure 3.3). When using SC, absolute errors increased with elevation angle, whereas errors were all within approximately a  $5^\circ$  range when using DC (Figure 4). Similar to mean error results, SC at maximum elevation resulted in consistently largest error. RMSE also displayed this pattern (Table 3.3).



**Figure 3.4: Absolute mean error for protraction (top), rotation (middle), and tilt (bottom). Values for 90° and maximum represent all participants, while values at 30°, 60°, and 120° are for 12 breast cancer survivors. Single calibration (SC) error was significantly higher than double calibration (DC) error. \*denotes significant differences.**

**Table 3.3: RMSE in degrees at each elevation level. Values at 90° and maximum include all 50 participants, while values at 30°, 60° and 120° represent 12 breast cancer survivors. SC = single calibration; DC = double calibration.**

Angle	DC	SC
Protraction 30	8.7	8.6
Rotation 30	3.7	4.5
Tilt 30	6.0	6.7
Actual Thoracohumeral Elevation	32.7	
Protraction 60	8.9	10.3
Rotation 60	6.1	9.3
Tilt 60	6.1	6.6
Actual Thoracohumeral Elevation	54.0	
Protraction 90	10.1	12.7
Rotation 90	9.0	11.2
Tilt 90	7.3	9.3
Actual Thoracohumeral Elevation	73.5	
Protraction 120	9.7	14.1
Rotation 120	10.9	12.3
Tilt 120	8.3	7.9
Actual Thoracohumeral Elevation	95.4	
Protraction Max	11.2	20.7
Rotation Max	5.4	18.3
Tilt Max	8.3	18.9
Actual Thoracohumeral Elevation	139	
Average RMSE		
Protraction	9.7	13.3
Rotation	7.0	11.1
Tilt	7.2	9.9

### ***3.4.2 Calibration and group***

Mean and absolute error levels were tested for group differences. There was no interaction or main effect of group. Errors were not different between breast cancer survivors and controls.

### 3.5 Discussion

This is one of the first studies to test the ability of the AMC to measure scapular motion on a clinical population. Breast cancer survivors were compared to controls of the same age group and disability score was the only difference between the two groups, with breast cancer survivors reporting higher disability of the upper limb. Although the AMC or similar placement with electromagnetic motion capture has been used on non-normative groups, the motions or analyses were limited to 120° of humeral elevation or static poses (Borstad & Szucs, 2012; Lukasiewicz, McClure, Lori Michener, Praff, & Senneff, 1999; McClure et al., 2006). The results from the current study indicate that the AMC is a viable method for dynamic scapular tracking of a clinical group.

DC generally had lower errors than SC. Scapular angle errors at maximum elevation using SC were higher (up to 12.9°) than errors at lower elevations and using DC. Improvements in RMSE when using DC coincide with a previous investigation comparing the two methods of calibration, although the errors in the current study are higher than reported in the aforementioned study (Brochard et al., 2011). Higher errors levels in the current study could be a result of methodical differences; during the dynamic elevations in Brochard et al. (2011), participants were asked to pause for 5 seconds at each elevation level used for comparison, while there were no pauses in the current study.

The error values when using DC in the current study are within the range of previously reported data of overall AMC accuracy. This persists (Table 3.4) despite several key methodological differences in the current study. First, all previous comparison investigations were performed with young participants ranging from adolescence to early 30s (Karduna et al., 2001; Maclean et

al., 2014; Meskers et al., 2007; Rapp et al., 2017; van Andel et al., 2009; Warner et al., 2012), while the average age of the current study was 52.8 years of age. Second, other testing has previously used a mix of young men and women (Karduna et al., 2001; Maclean et al., 2014; Meskers et al., 2007; Rapp et al., 2017; van Andel et al., 2009; Warner et al., 2012), compared to the all-female group in the current study. Younger participants and the inclusion of men likely influenced the results; both of these factors suggest that participants in previous literature were leaner, although most studies did not provide height and weight information for a direct comparison. The sample in the current study had an average BMI of 26.8, with 30 participants having BMIs classified as “overweight” and 11 considered “obese” (Jensen et al., 2014), suggesting increased adipose tissue around the shoulder that would affect scapular motion tracking. Leaner participants would facilitate the palpation of scapular landmarks during static trials and indicate that there is less tissue present around the shoulder that could affect AMC movement over the acromion. However, use of the DC method appears to mitigate the possible body composition effect on tracking errors. Finally, the current study tested the ability of the AMC to track scapular motion throughout the participant’s full range of motion (average maximum ROM =  $139^{\circ}$  [ $104^{\circ}$ ,  $166^{\circ}$ ]), while the AMC has largely only been tested up to approximately  $120^{\circ}$  (Maclean et al., 2014; van Andel et al., 2009; Warner et al., 2012). These results indicate that double calibration can be used above  $120^{\circ}$  and remain within currently accepted error levels.

**Table 3.4: Comparison of studies that have investigated the accuracy of the AMC method during arm elevation, including the present study.**

<b>Authors</b>	<b>Method of validation</b>	<b>Humeral elevation levels (°)</b>	<b>Results</b>
<b>Karduna et al. (2001)</b>	Bone pins vs AMC electromagnetic	0-150	Average RMSE 10° Pro 4.8° UR 7.3° PT
<b>Meskers et al. (2007)</b>	Locator vs AMC electromagnetic	30-130	Max mean error 13°
<b>Van Andel et al. (2009)</b>	Locator vs AMC electromagnetic	0-120	Max mean error 6°
<b>Warner et al. (2012)</b>	Locator vs AMC marker cluster – lowering	0-120	Average RMSE 4.0° Pro 6.0° UR 7.2° PT
<b>MacLean et al. (2014)</b>	Palpated digitizer vs AMC marker cluster	10-120	Max mean error -10.6°
<b>Rapp et al. (2017)</b>	Palpated orientations vs AMC marker cluster	5 test positions	Max RMSE 11.8° Max mean error -9.6°
<b>Current study</b>	Palpated orientations vs AMC marker cluster	30-maximum	Average RMSE 9.9° Pro 6.4° UR 7.2° PT Max mean error 8.7°
		90, maximum	10.6° Pro 7.2° UR 7.8° PT Max mean error 6.1°

AMC=\_\_acromion marker cluster\_\_

RMSE =Root mean square error

Pro = scapular protraction/retraction

UR = scapular upward rotation

PT = scapular posterior/anterior tilt



The AMC with DC estimated scapular upward rotation the most accurately and consistently. Upward rotation has been identified as the most important scapular degree of freedom for understanding shoulder dysfunction (Fouad Fayad et al., 2008). Alterations in upward rotation from typical patterns has been implicated in the development of rotator cuff impingement (Ludewig & Reynolds, 2009) and is the most commonly evaluated movement in a clinical setting in order to determine scapular asymmetry or dyskinesis (M. P. Johnson et al., 2001; Kibler et al., 2013; Struyf et al., 2012). Changes in upward rotation are reported following breast cancer treatment (Crosbie et al., 2010), indicating this measure is important to track in this population. While definitive recommendations for other individuals with shoulder pathologies cannot be made from these results, satisfactory performance of the AMC for upward rotation measurement encourages its use for measurement and interpretation for clinical populations.

While the error values are within the range of data reported from younger, pathology-free populations, the levels of error still indicate the AMC is not a perfect measurement tool. Differences in scapular angles in pathological groups have historically been small (McClure et al., 2006), and alterations caused by breast cancer treatment may be modest; changes in scapular angles could range from 3-12° (Borstad & Szucs, 2012; Crosbie et al., 2010; Shamley et al., 2008). While it is unclear what magnitude of change is important during scapular movement, error levels of 10.6°, such as protraction RMSE for the current participants, indicate that differences must be substantial to confidently identify scapulothoracic kinematic compensations. This potentially high magnitude of detectable change could pose problems for researchers and clinicians alike when attempting to understand important kinematic alterations.

Some methodical considerations limit the interpretation of these results. Scapular angles from dynamic trials were compared to palpations from static poses, as opposed to the gold standard of

bone pins. However, comparison to palpation is a method that has been used previously (Maclean et al., 2014; Rapp et al., 2017) to replace bone pins due to the practical and ethical difficulty of using pins. It should be noted, though, that comparing to static palpations introduces the possibility that some of the AMC error could be related to static versus dynamic differences (Maclean et al., 2014). The speed of arm movement was also not controlled during dynamic trials in the present study; participants were instructed to move at a comfortable pace. Finally, breast cancer survivors and age-matched controls were not directly compared to a younger population. It is possible that direct comparison with the same methods would demonstrate error magnitude differences between populations.

### **3.6 Conclusions**

The AMC with DC supplies a low-error, non-invasive method for measurement and subsequent comparison of scapular orientations of breast cancer survivors and age matched controls. These results can help guide evaluation and interpretation of scapulothoracic kinematics of breast cancer survivors during dynamic task performance, ultimately providing better evidence for rehabilitation and treatment options for those with upper limb disorders.

## **TRANSITION FROM CHAPTER 3 TO CHAPTER 4**

Manuscript 1 demonstrated that scapula motion of breast cancer survivors and age-group-matched controls can be tracked with reasonable accuracy by using the AMC with a double calibration technique. Testing this motion tracking method provides confidence when using this method to measure upper limb motion in breast cancer survivors during a variety of tasks.

Many investigations of scapular motion for any sample, healthy or pathological, have focused on arm motion below 120° of elevation. The method outlined in the above manuscript can be used to measure scapular motion through full elevation and other tasks that are performed throughout the full arm elevation range of motion. Measured scapular data provides valuable information for several clinical and fundamental biomechanical questions.

The next manuscript will examine upper limb kinematics, including scapular motion, of breast cancer survivors during functional task performance. This novel research aims to define movement strategies in an unprecedented functional protocol to improve understanding of shoulder function and the biomechanical risk factors for future injury in breast cancer survivors.

## **CHAPTER 4: IMPINGEMENT PAIN AFFECTS KINEMATICS OF BREAST CANCER SURVIVORS IN WORK-RELATED FUNCTIONAL TASKS**

Angelica E Lang<sup>1</sup>, Clark R Dickerson<sup>2</sup>, Soo Y Kim<sup>3</sup>, Jamie Stobart<sup>3</sup>, Stephan Milosavljevic<sup>3</sup>

<sup>1</sup> Department of Health Sciences, College of Medicine, University of Saskatchewan, Canada

<sup>2</sup>Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, Canada

<sup>3</sup> School of Rehabilitation Science, College of Medicine, University of Saskatchewan, Canada

### **Contribution:**

Angelica Lang was a primary contributor to the study conception and design. She led and completed all participant recruitment, data collection sessions, and data analysis. She was also the primary author of the manuscript.

### **Publishing status:**

This article was published in Clinical Biomechanics:

**Lang, A.E.**, Dickerson, C.R, Kim, S.Y., Stobart, J., & Milosavljevic, S.M. (2019). Impingement pain affects kinematics of breast cancer survivors in work-related functional tasks. *Clinical Biomechanics*. 70: 223-230.

## 4.1 Abstract

**Background:** Breast cancer survivors may encounter upper limb morbidities post-surgery. It is currently unclear how these impairments affect arm kinematics, particularly during functional task performance. This investigation examined upper body kinematics during functional tasks for breast cancer survivors and an age-matched control group.

**Methods:** Fifty women (aged 35-65) participated: 25 breast cancer survivors who had undergone mastectomy and 25 age-range matched controls. Following basic clinical evaluation including shoulder impingement tests, motion of the torso and upper limbs was tracked during six upper limb-focused functional tasks from which torso, scapular, and thoracohumeral angles were calculated. Between-group differences were evaluated with independent t-tests ( $p < 0.05$ ). The breast cancer group was then divided based upon impingement tests and differences between the three new groups were tested with one-way ANOVAs ( $p < 0.05$ ).

**Findings:** Breast cancer survivors had higher disability scores, lower range of motion, and lower performance scores. The largest kinematic differences existed between the breast cancer survivors with impingement pain and the two non-pain groups. During overhead tasks, right peak scapular upward rotation was significantly reduced (Cohen's  $d = 0.80-1.11$ ) in the breast cancer survivors with impingement pain. This group also demonstrated trends of decreased peak humeral abduction and internal rotation at extreme postures (Cohen's  $d = 0.54-0.78$ ). These alterations are consistent with kinematics considered high risk for rotator cuff injury development.

**Interpretation:** Findings suggest that impingement pain in breast cancer survivors influences functional task performance and may be more important to consider than self-reported disability when evaluating pain and potential injury development.

## 4.2 Introduction

Breast cancer survivors often experience upper limb functional deficits. Problems such as reduced range of motion, reduced strength, lymphoedema, and pain are common following surgery and can last for years after curative treatment (Hack et al., 1999; Sagen et al., 2014). The presence of arm limitations suggest potential biomechanical changes at the shoulder that could affect abilities and increase risk of future injury, supported by the higher rates of secondary morbidities present in breast cancer survivors compared to non-cancer controls (Borstad & Szucs, 2012; Shamley et al., 2012; Yang et al., 2010). In particular, it has been hypothesized that breast cancer survivors are at increased risk of developing rotator cuff disease, which for this paper will be used as a term encompassing a wide range of tendinopathies of the rotator cuff, including subacromial impingement and related pain of the shoulder (Ebaugh et al., 2011; Yang et al., 2010). While this relationship has yet to be conclusively demonstrated, there is evidence that upper limb dysfunction during early recovery from breast cancer treatment is associated with high rates of rotator cuff disease in the longer term (Yang et al., 2010), suggesting this relationship warrants further investigation.

Rotator cuff disease is the most prevalent musculoskeletal disorder of the shoulder (Mitchell, Adebajo, Hay, & Carr, 2005). Symptomatic rotator cuff disease causes pain and motion restriction (Yamaguchi et al., 2000) and is associated with altered kinematics of the shoulder. Individuals diagnosed with rotator cuff disease generally demonstrate decreased upward rotation, decreased posterior tilt, and increased internal rotation and elevation of the scapula (Lin, Kim, & Yang, 2006; Ludewig & Cook, 2000; Ludewig & Reynolds, 2009). Increased humeral internal rotation is also associated with rotator cuff disease. Similar kinematic strategies exist in breast

cancer survivors (Borstad & Szucs, 2012; Brookham et al., 2018a; Shamley et al., 2008), suggesting a predisposition to rotator cuff disease development which can exacerbate arm dysfunction.

Shoulder kinematic investigations predominantly examine arm elevation. Indeed, few studies exist on shoulder kinematics of breast cancer survivors during arm-focused functional tasks (Brookham et al., 2018a; Spinelli, Silfies, Jacobs, Brooks, & Ebaugh, 2016), and none reporting kinematics during functional, return-to-work specific tasks for any shoulder pathological groups. Due to known range of motion and strength challenges reported by breast cancer survivors, they may adopt altered compensatory movement strategies to complete functional tasks (Côté et al., 2005; Hamill, Van Emmerik, Heiderscheit, & Li, 2009). These potential strategies could then overload other tissues that are usually not involved. For instance, individuals with shoulder pain often decrease shoulder range of motion but increase trunk motion to complete reaching movements (Lomond & Côté, 2011; McClure et al., 2006; Roy et al., 2008). Identifying potentially high-risk movement strategies allows for improved treatment and evidence-based return-to-work recommendations.

Improved characterization of shoulder movement strategies during work-related functional tasks will not only improve primary understanding of shoulder biomechanics of breast cancer survivors, but also provide direction for rehabilitative and return-to-work recommendations following breast cancer treatment. Comparing kinematics of breast cancer survivors and non-cancer control groups can reveal the presence of alterations related to future injury risk. Thus, the purpose of this study was to define torso and shoulder kinematics during common arm-centric, goal-directed tasks and compare them between breast cancer survivors and non-cancer control groups. It was hypothesized that breast cancer survivors would use different kinematic strategies;

particularly, breast cancer survivors would decrease the contribution of the shoulder and increase torso range of motion (Lomond & Côté, 2011), while also demonstrating scapular and humeral alterations consistent with rotator cuff disease.

### **4.3 Methods**

#### ***4.3.1 Participants***

Fifty women participated: 25 breast cancer survivors and 25 age-group-matched controls. All participants were aged 35-65 years. Breast cancer survivors who were diagnosed with either unilateral or bilateral cancer and had undergone mastectomy surgery at least 6 months prior to participation were recruited from the community. Breast cancer survivors who had breast reconstruction of any type were excluded. The control group consisted of a convenience sample of women who were free from upper limb impairments. Although participants were not prospectively recruited based on evidence of pain, the presence or absence of impingement pain in both groups was confirmed with a series of clinical tests (Neers' Impingement test, Hawkins-Kennedy Impingement, and empty can test) (Calis, 2000; Moen et al., 2010). A positive result on any test warranted exclusion from the control group. Other exclusion criteria for both groups included: previous shoulder surgery, inability to raise arms overhead, and allergies to rubbing alcohol or skin adhesives.

#### ***4.3.2 Instrumentation***

Motion of the thorax, scapulae, humeri, and pelvis was tracked using 10 VICON MX20 (Vicon Motion Systems, Oxford, UK) optoelectronic infrared cameras positioned around the collection space. Thirty-six reflective markers were placed on the torso and upper extremity in the form of individual markers and rigid clusters, with an extra six virtual markers representing the



anatomical points of the scapulae. An acromial marker cluster (AMC) was used to track the scapula (Lang, Kim, Milosavljevic, & Dickerson, 2019). All individual markers were placed at anatomical points based on International Society of Biomechanics recommendations (G. Wu et al., 2005). The collection space was calibrated prior to each collection and position of the markers were sampled at 50 Hz.

#### ***4.3.3 Experimental Protocol***

Prior to testing, participants provided informed consent and completed the Quick Disability of the Arm, Shoulder and Hand (QuickDASH) and the Physical Activity Readiness Questionnaire (PAR-Q). Next, participants were equipped with markers for motion capture. The AMC was calibrated with a double calibration method involving digitization of anatomical points with the arm at neutral and maximum elevation (Brochard et al., 2011; Lang, Kim, et al., 2019).

The experimental protocol included six work-related functional tasks. The functional activities were chosen to represent tasks that are commonly used to evaluate the upper limb in a clinical environment, specifically for return-to-work. This selection of tasks tests the whole upper limb, including speed and coordination of arm and hand movement, gross movement of the fingers, hands and arms, functional strength, and postural tolerance (Reneman, Soer, & Gerrits, 2005; Soer et al., 2009), combined with assessment of kinematics in three planes of motion. There is no universal standard for assessment of upper limb function, but this task battery covers the main aspects that are often evaluated for return-to-work. The reliability of most tasks is established (Reneman et al., 2005) and they are easily and safely administered in the lab setting with equipment that is readily available to researchers and clinicians alike. The functional task procedures were similar to those reported in Lang and Dickerson (Lang & Dickerson, 2017a, 2017b), with minor differences in equipment height and subtask selection. The tasks were

performed in the same order for each participant, to mimic a return-to-work evaluation as closely as possible (Table 4.1).

**Table 4.1: Order of task performance for each collection. All subtasks were performed 3 times unless otherwise specified.**

Order	Task	Subtask/Set up
1	Overhead reach	<ul style="list-style-type: none"> <li>▪ Right hand <ul style="list-style-type: none"> <li>- Unloaded</li> <li>- Loaded</li> </ul> </li> <li>▪ Left hand <ul style="list-style-type: none"> <li>- Unloaded</li> <li>- Loaded</li> </ul> </li> </ul>
2	Repetitive reach	<ul style="list-style-type: none"> <li>▪ Right hand</li> <li>▪ Left hand</li> </ul>
3	Fingertip dexterity	<ul style="list-style-type: none"> <li>▪ Right hand</li> <li>▪ Left hand</li> <li>▪ Both hands</li> </ul>
4	Hand and forearm dexterity	<ul style="list-style-type: none"> <li>▪ Right hand</li> <li>▪ Left hand</li> </ul>
5	Waist to overhead lift	<ul style="list-style-type: none"> <li>▪ Three sets of five</li> </ul>
6	Overhead work	<ul style="list-style-type: none"> <li>▪ As long as possible (15 minute cap)</li> </ul>

The first task was the overhead reach. Participants sat in front of a set of shelves and reached towards a target on a shelf that was centred in front of their body, 1.5 m off the ground (Brookham et al., 2018a). The reach was performed both unloaded and holding a 1 kg load. Each reach was performed one arm at a time, with three repetitions for each arm.

The repetitive reaching task required two bowls positioned at the wingspan of each participant while sitting (Reneman et al., 2005). Thirty marbles were placed in one bowl and the participant was ask to move the marbles horizontally, one at time, from one bowl to the other as quickly as possible. Marbles were always moved from right to left, three times with each hand. The time to complete the three sets was averaged and recorded as a performance measure.

The Purdue Peg Board Test was used for the fingertip dexterity task (Lafayette Instrument, 2002). The participant sat in front of the peg board and placed the pins as quickly as possible into the holes for 30 seconds in three subtasks: right hand, left hand, and both hands. Each subtask was repeated three times. The final performance measure was the average number of pegs for the three sets of each subtask.

The Minnesota Manual Dexterity Test placing test was used for the hand and forearm dexterity task (Lafayette Instrument, 1998). Participants were required to move blocks into a board in a predetermined pattern as quickly as possible. This placing task traditionally only requires the use of the dominant hand, but to test the effects of potential lateralized impairments, both hands were tested. The performance measure was the average time of all three sets of each subtask.

The next task in the evaluation protocol was the overhead lift. This lifting procedure traditionally requires the patient to do four sets of lifts with increasing intensity until a maximum is reached (Reneman et al., 2005). For this data collection, participants only performed lifts at one intensity; the load was set to 8 kg, equal to 50% of the maximum capacity of the normative dataset collected by Lang & Dickerson (Lang & Dickerson, 2017b). While standing, each participant lifted a standard sized milk crate with both hands from a shelf set to waist height to a shelf set at forehead height. This movement was repeated five times. Three sets were performed to remain consistent with the rest of the protocol.

Finally, the prolonged overhead work task required participants to manipulate objects at their forehead height until exhaustion. Participants were asked to stand in front of the forehead height shelf wearing 1 kg cuff weights. They manipulated nuts and bolts at the height of the shelf until they could no longer hold the desired position (Reneman et al., 2005).

#### **4.3.4 Data Processing**

Kinematic data were processed with a custom MATLAB® code. All raw kinematic data were filtered with a low-pass, zero-lag, fourth-order Butterworth filter with a 6 Hz cut-off (Winter, 2009). The filtered data were used to create local coordinate systems of each segment. The glenohumeral joint was calculated as 60 mm below the acromion parallel to the Y vector of the torso (Nussbaum & Zhang, 2000).

Joint coordinate systems were used to describe clinically relevant rotations. Torso (defined as the thorax relative to pelvis) rotations were extracted using the Z-X'-Y'' Euler sequence and were described as flexion/extension, lateral flexion/extension, and axial rotation (G. Wu et al., 2005). Thoracohumeral (humerus relative to the thorax) rotations were calculated with the X-Z'-Y'' sequence and were described as abduction/adduction, flexion/extension, and internal/external rotation (Phadke, Braman, LaPrade, & Ludewig, 2011). Right thoracohumeral abduction/adduction and left internal/external rotation were adjusted so abduction and internal rotation were always positive. Scapula (scapula relative to torso) rotations used the Y-X'-Z'' Euler sequence and were described as protraction/retraction, upward/downward rotation, and anterior/posterior tilt. Right rotation was adjusted so upward rotation was always positive.

Cycles during each task were identified using equipment reference markers (similar to Lang & Dickerson (Lang & Dickerson, 2017a, 2017b)). An equipment calibration was performed prior to task performance, during which reflective markers were placed at the position of the equipment (i.e. the bowls for the repetitive reaching task, the shelves for the overhead lift, etc.). Cycles were then identified by locating when the hand markers passed the position of the marker in the direction of movement. For the repetitive reach, fingertip dexterity, and hand and forearm dexterity tasks, a movement cycle was defined as the time during which the arm moved from the

starting position and back. For the overhead reach and overhead lift, a cycle was defined as the time during which participants moved their hand or the load from the low shelf placed it on the high shelf. The overhead work had no defined cycles, so the first and last 30-second sections were analyzed.

#### ***4.3.5 Statistical Analysis***

Descriptive statistics (mean, maximum, and minimum values) for all angles were calculated for each participant and task. Independent t-tests were used to test the effect of group on each outcome variable. Main effects were assessed at the 5% significance level. A post-hoc analysis division of breast cancer survivors by impingement pain was performed to determine the effects of pain on breast cancer survivor movement; one-way fixed-effect ANOVAs were used to test the effects of impingement pain on each shoulder angle variable for controls and the two breast cancer groups and post-hoc Tukey HSD were used to confirm significant differences.

#### **4.4 Results**

Breast cancer survivors presented with several clinically important differences in personal characteristics compared to non-cancer controls. While age, height, and weight were not different between the two groups, breast cancer survivors reported higher disability scores and demonstrated reduced humeral elevation and extension range of motion (Table 4.2). Thirteen breast cancer survivors reported pain on at least one impingement screening test, for a total of 17 shoulders with at least one positive (BC+). Finally, breast cancer survivors had lower performance scores on all functional tasks than controls; when divided by presence of impingement pain (BC- or BC+), BC+ performance scores were consistently the lowest (Table 4.3).

**Table 4.2: Participant demographic and clinical information for controls and breast cancer survivors with (BC+) and without (BC-) impingement pain.**

	<b>Control (n = 25)</b> <b>Mean (SD)</b>	<b>BC - (n = 12)</b> <b>Mean (SD)</b>	<b>BC + (n=13)</b> <b>Mean (SD)</b>	<b><i>p</i></b>
<b>Age</b>	51.6 (7.0)	52.8 (5.4)	55.2 (5.0)	.244
<b>Height (m)</b>	1.62 (0.08)	1.61 (0.07)	1.61 (0.04)	.769
<b>Weight (kg)</b>	68.7 (11.8)	75.8 (17.4)	69.1 (13.1)	.308
<b>Dominance (R/L)</b>	23/2	12/0	13/0	-
<b>DASH (/100)*</b>	4.7 (6.3)	14.4 (13.4)	18.9 (7.0)	.000
<b>Neers' sign (# of +ves)</b>	0	0	4	-
<b>Hawkins-Kennedy (# of +ves)</b>	0	0	6	-
<b>Empty can (# of +ves)</b>	0	0	10	-
<b>Elevation range of motion (°)*</b>	150.4 (12.3)	141.4 (34.7)	146.8 (14.1)	.011
<b>Extension range of motion (°)*</b>	48.2 (13.8)	32.3 (13.3)	39.3 (16.9)	.000
<b>Surgery side (R/L)</b>	-	10/9	9/8	
<b>Lymph node removal (/25)</b>	-	11	13	-
<b>Chemotherapy (/25)</b>	-	10	10	-
<b>Radiation (/25)</b>	-	7	8	-
<b>Time since surgery (months)</b>	-	42.5 (41.6)	70.0 (39.7)	.105

\*denotes significant difference between both breast cancer survivors groups and controls from one-way ANOVA ( $p < .05$ )

**Table 4.3: Performance results for controls and breast cancer survivors with (BC+) and without (BC-) impingement pain.**

<b>Task</b>	<b>Control (n = 25) Mean (SD)</b>	<b>BC – (n = 12) Mean (SD)</b>	<b>BC + (n=13) Mean (SD)</b>	<b>Sig.</b>
<b>Repetitive reaching right * (s)</b>	53.6 (6.6)	56.0 (6.2)	61.4 (8.8)	.011
<b>Repetitive reaching left * (s)</b>	52.5 (6.3)	58.2 (7.9)	62.5 (10.2)	.002
<b>Fingertip dexterity right § (# pins)</b>	17.1 (1.9)	17.1 (1.8)	15.3 (1.7)	.011
<b>Fingertip dexterity left § (# pins)</b>	16.6 (1.5)	16.1 (1.5)	14.6 (2.2)	.004
<b>Fingertip dexterity both § (# pins)</b>	13.5 (1.5)	13.7 (1.2)	11.9 (1.4)	.003
<b>Hand and forearm dexterity right (s)</b>	65.3 (8.2)	65.5 (5.8)	70.4 (11.9)	.213
<b>Hand and forearm dexterity left (s)</b>	67.9 (10.5)	68.0 (7.3)	75.2 (12.8)	.110
<b>Overhead lift (kg)</b>	8.0 (0)	7.6 (1.3)	7.4 (2.2)	.355
<b>Overhead work<sup>+</sup> (s)</b>	258.2 (135.1)	179.5 (68.8)	190.2 (119.3)	.033

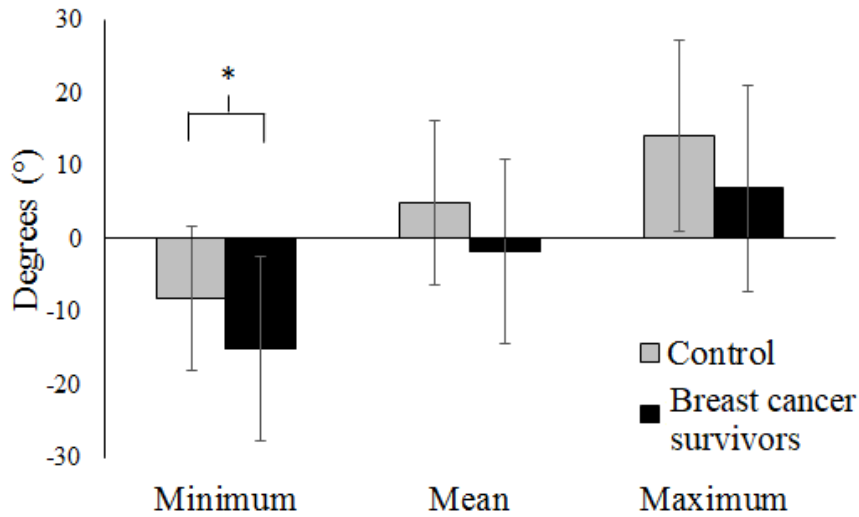
\*denotes significant difference between BC+ and controls.

§denotes significant difference between BC+ and both BC- and controls.

<sup>+</sup>denotes significant difference between both breast cancer survivor groups and controls

#### **4.4.1 Breast cancer survivors vs controls**

Breast cancer survivors as one group displayed thoracic kinematic alterations during performance of the overhead reach and overhead lift tasks that were not present when divided by impingement pain. During the overhead reach, breast cancer survivors' torsos were less laterally bent to the right (control vs breast cancer survivors: 4.3° vs -0.4°, Cohen's  $d = 0.61$ ,  $p = 0.000$ ) throughout all subtasks. In the overhead lift, breast cancer survivors demonstrated increased torso flexion ( $d = 0.60$ ,  $p = 0.045$ ) (Figure 4.1).

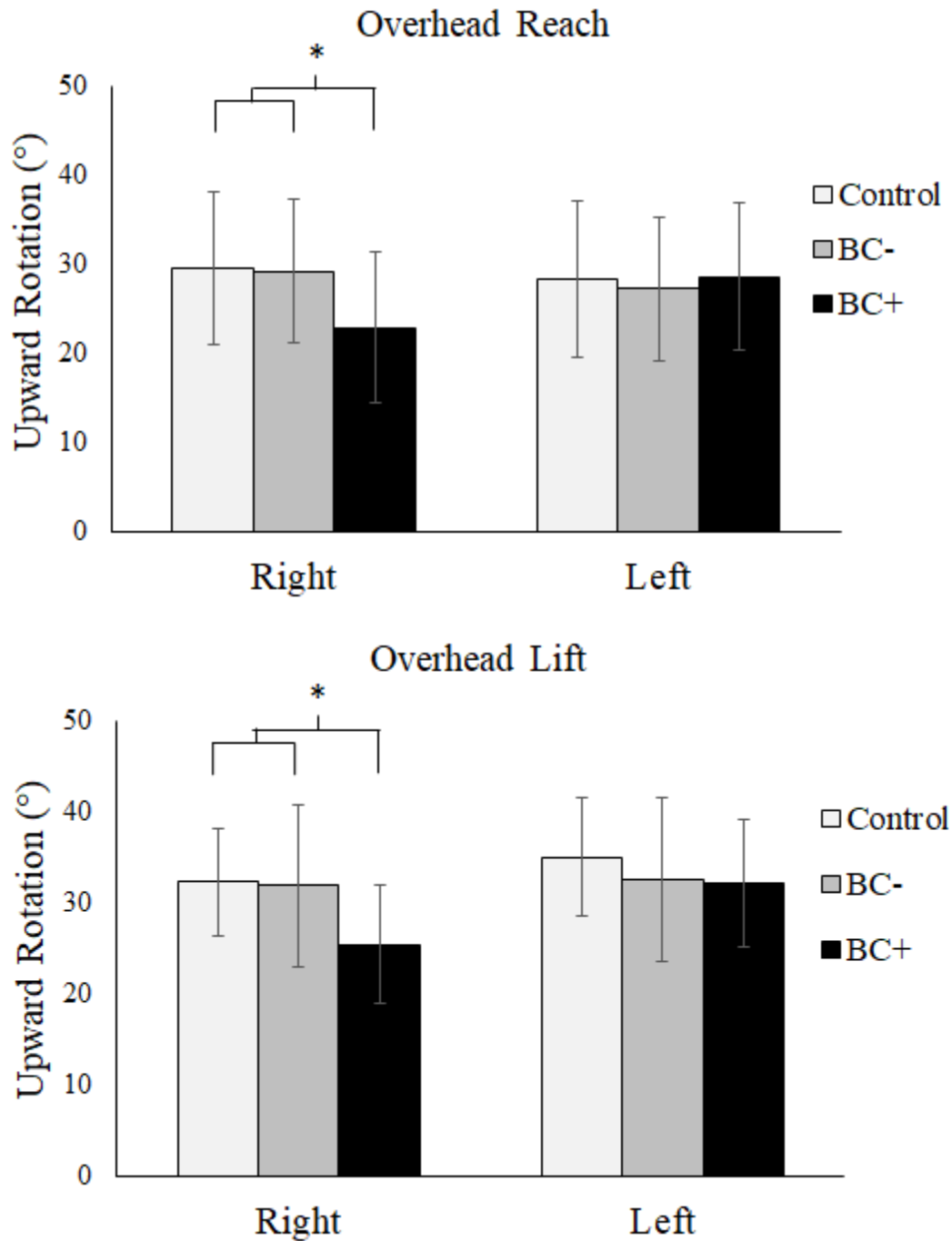


**Figure 4.1: Minimum, mean and maximum (with standard deviation) torso flexion/extension (-ve = flexion, +ve = extension) during the overhead lift. Minimum angles (maximum flexion) were significantly different between groups.**

#### ***4.4.2 Impingement pain vs controls***

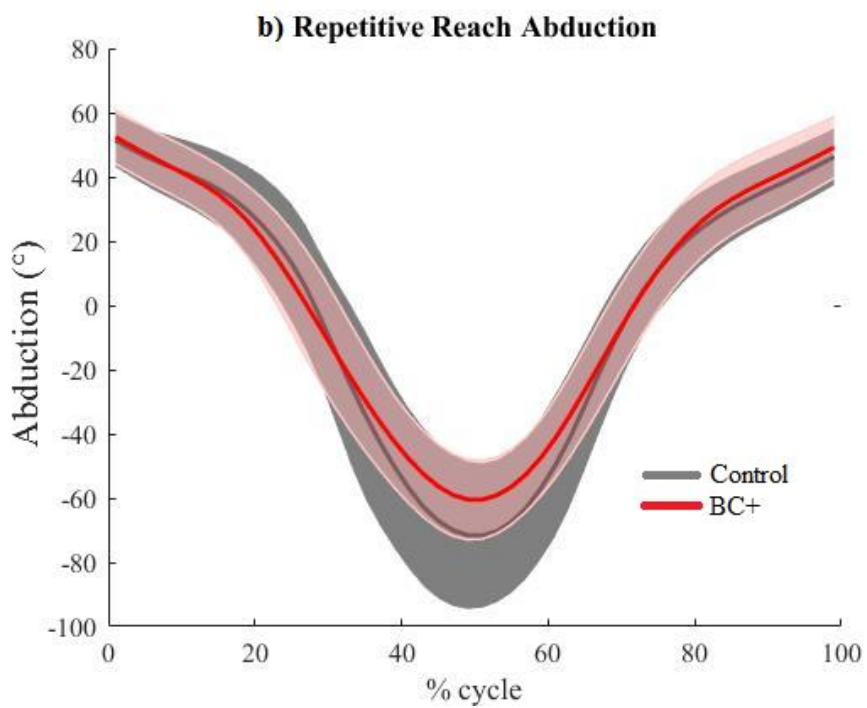
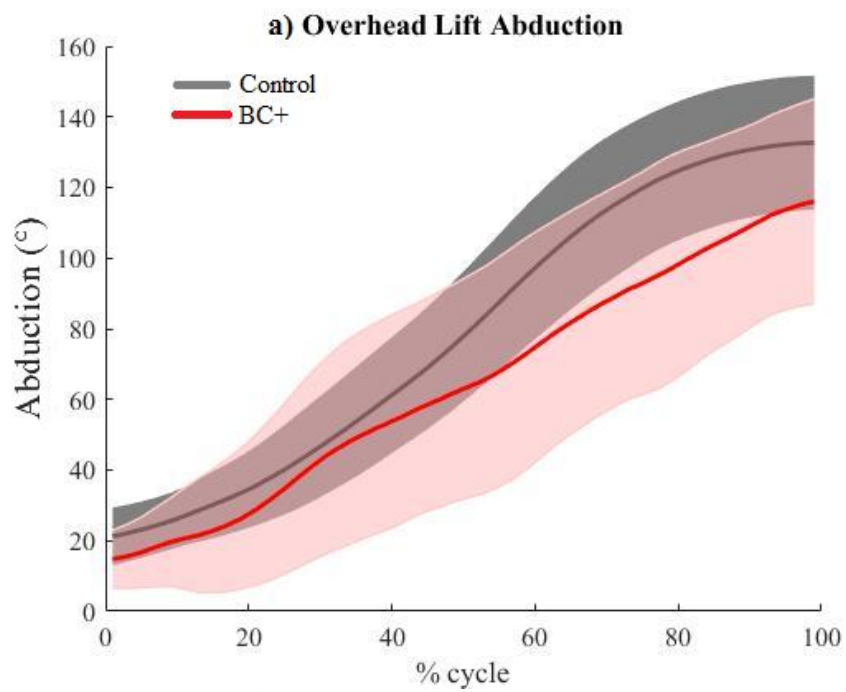
When breast cancer survivors were subdivided by presence of impingement pain (BC- and BC+), greater scapular and humeral kinematic alterations existed for the overhead reach, repetitive reaching task, and overhead lift, but not for the fingertip or hand and forearm dexterity tasks (Table 4.4). During the overhead reach and lift tasks, BC+ had less right maximum scapular upward rotation than controls and BC- (Reach  $d = 0.80$ ,  $p = 0.006$ ; Lift  $d = 1.11$ ,  $p = 0.027$ ;) with the largest difference of  $11.2^\circ$  detected at the right scapula during the overhead lift (Figure 4.2).

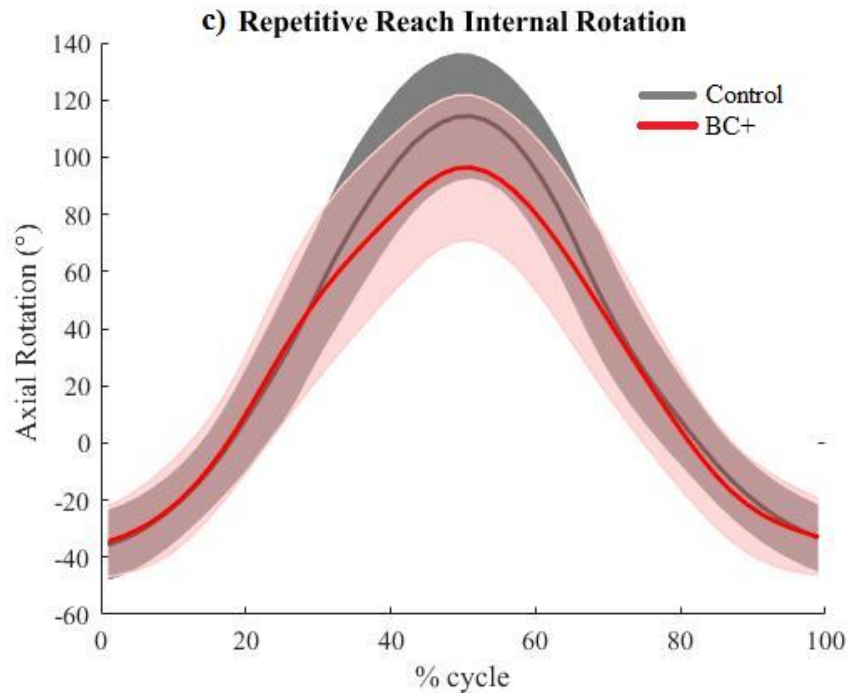




**Figure 4.2:** Maximum scapular upward rotation (with standard deviation) for the overhead reach and lift tasks. Upward rotation on the right side was significantly lower for BC+ (breast cancer survivors with impingement pain) than the other groups in all tasks.

Trends for humeral kinematics suggest that BC+ compensated at the thoracohumeral joint during the repetitive reaching task and overhead lift. During the overhead lift, BC+ maximum right side abduction was lower than controls ( $d = 0.54$ ,  $p = 0.114$ ) (Figure 4.3a). During the repetitive reaching task, BC+ humeral angles were reduced compared to controls in minimum right side humeral abduction (maximum adduction) (Figure 4.3b) and maximum right side humeral internal rotation (Figure 4.3c), the combined humeral position during cross body marble drop. Due to high inter-subject variability in angles, these did not reach significance, but effect sizes suggest a medium to large effect (Abduction  $d = 0.57$ ,  $p = 0.351$ , Rotation  $d = 0.78$ ,  $p = 0.122$ ) (Figure 3b,c).





**Figure 4.3: Mean (solid lines)  $\pm$  1 SD (shaded areas) waveforms for humeral abduction in the overhead lift (a), humeral abduction in the repetitive reach (b) and humeral axial rotation in the repetitive reach (c). Y axis represents the time to complete one full movement cycle (i.e. one lift or one reach). Positive values represent abduction and internal rotation, while negative values represent adduction and external rotation. BC+ (breast cancer survivors with impingement pain) were consistently in less extreme humeral postures during the peaks of the movements (end of the lift, middle of the repetitive reach).**

**Table 4.4: Summary of kinematic differences between three groups (BC+ = breast cancer survivors with impingement pain, BC- = breast cancer survivors without (BC-) impingement pain). Values not connected with the same letter are significantly different.**

Task	Variable	Group	Angle (°) Mean (SD)
Overhead reach	Mean torso lateral flexion	Control	4.3 (9.3) <sup>a</sup>
		BC-	0.1 (5.3) <sup>b</sup>
		BC+	-1.1 (5.7) <sup>b</sup>
	Maximum right scapular upward rotation	Control	29.5 (8.6) <sup>a</sup>
		BC-	29.2 (8.1) <sup>a</sup>
		BC+	22.9 (8.5) <sup>b</sup>
Overhead lift	Maximum torso flexion	Control	-8.4 (9.9) <sup>a</sup>
		BC-	-16.2 (15.7) <sup>b</sup>
		BC+	-14.1 (9.9) <sup>b</sup>
	Maximum right scapular upward rotation	Control	32.3 (5.9) <sup>a</sup>
		BC-	31.9 (8.9) <sup>a</sup>
		BC+	25.4 (6.5) <sup>b</sup>
Repetitive reach	Maximum right humeral abduction	Control	133.8 (19.6)
		BC-	134.8 (15.3)
		BC+	121.7 (24.3)
	Maximum right humeral adduction	Control	-73 (25.0)
		BC-	-65.4 (30.0)
		BC+	-61.6 (12.6)
	Maximum right humeral internal rotation	Control	117.8 (24.3)
		BC-	113.4 (24.5)
		BC+	97.6 (25.7)

## 4.5 Discussion

Several clinical and kinematic differences emerged between breast cancer survivors who had undergone mastectomies and age-group-matched non-cancer controls. Although all breast cancer survivors were able to complete all the work-related functional tasks, they reported higher disability and their performance scores were lower than controls. Kinematic alterations occurred in scapulothoracic and thoracohumeral motions of BC+ (breast cancer survivors who reported

pain during at least one impingement test) during overhead tasks. This group also averaged 14.4% lower performance scores than both controls and BC- (breast cancer survivors without impingement pain).

The presence of impingement pain was the most influential factor on kinematics. Kinematics consistently differed between BC+ and controls. Most notably, BC+ scapular upward rotation was reduced during the overhead reach and lift tasks. The magnitude of the angular differences when impingement pain was considered was greater than the RMSE of AMC ( $5.4^{\circ}$ ) (Lang, Kim, et al., 2019), providing confidence that the differences relate to pathology and not measurement error. Upward rotation alterations are important with regards to rotator cuff injury development; decreases in upward rotation are commonly present in persons diagnosed with rotator cuff disease (Keshavarz, Bashardoust Tajali, Mir, & Ashrafi, 2017; Ludewig & Cook, 2000; Turgut, Duzgun, & Baltaci, 2016) and inadequate upward rotation can reduce the size of the subacromial space, possibly causing the impingement of the supraspinatus tendon (Brossmann et al., 1996). Because all BC+ participants only reported pain on one or two tests (participants with positive results on 1 test = 7; 2 tests = 6; 3 tests = 0), many may not yet meet diagnosis criteria for rotator cuff disease. Thus, the scapular alterations could be important to monitor through the long-term recovery from breast cancer surgery for rotator cuff disease development.

The distinct differences in humeral kinematics during task performance also provides insight into compensations from impingement pain in post-mastectomy breast cancer survivors. During the repetitive reach, peak humeral internal rotation was lower in the BC+ group, which coincides with a compensation strategy to avoid impinging the supraspinatus tendon, as tendon contact area increases with humeral internal rotation (Brossmann et al., 1996). Humeral abduction in the overhead lift and adduction (reaching across the body) in the repetitive reaching task were also

both lower in BC+. This could reflect pain avoidance, tightness, or weakness at the shoulder, all commonly experienced by breast cancer survivors (Assis et al., 2013; Lang et al., n.d.), which could also contribute to the development of rotator cuff disease (Ebaugh et al., 2011).

While this work demonstrates novel kinematic alterations in breast cancer survivors with impingement pain, it is also one of the first works to report a preliminary prevalence of impingement pain in a convenience sample of post-mastectomy breast cancer survivors. It was previously suggested that breast cancer survivors would be at risk for rotator cuff disease as a result of the physical side effects of treatment (Ebaugh et al., 2011), and the current investigation suggests approximately 50% will present with impingement-related pain in the years following mastectomy. Considering the age of the participants (Table 4.2), this is a high rate of pain in an already compromised population (Milgrom, Schaffler, Gilbert, & van Holsbeeck, 1995).

Therefore, the factors contributing to the development of rotator cuff disease in breast cancer survivors, such as the compromised scapular movement patterns presented in this paper, are important to investigate further for shoulder health, daily life, and return-to-work in breast cancer survivors.

It was hypothesized that breast cancer survivors would decrease the contribution of the thoracohumeral joint and increase torso motion to complete these functional tasks. While there are some humeral alterations as mentioned above, corresponding kinematic compensations at the trunk were minimal. For the overhead lift, breast cancer survivors may have adjusted by increasing trunk momentum. Torso flexion was higher in breast cancer survivors at the start of the overhead lift, and this same alteration was seen in a young normative kinematic dataset as the intensity of the lift increased (Lang & Dickerson, 2017b). It was postulated that the compensation in the younger population was an attempt to use momentum and shift the load to

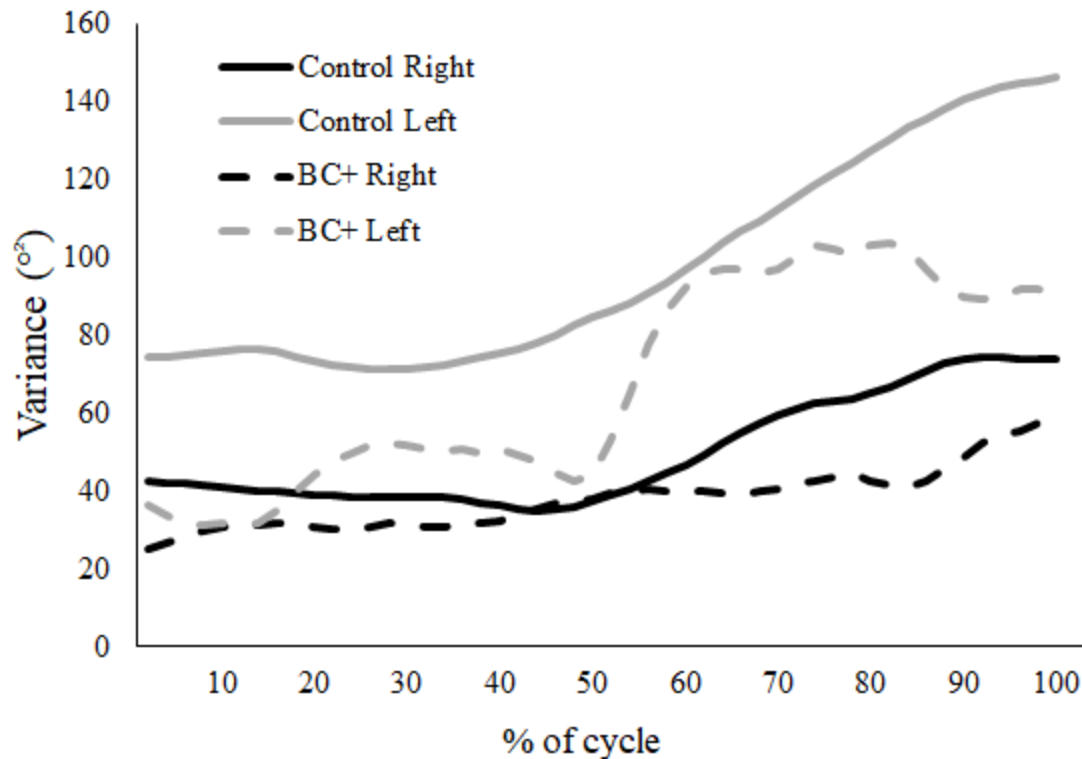
the larger back muscles (Arjmand & Shirazi-Adl, 2005; Callaghan, Gunning, & McGill, 1998; Howarth & Callaghan, 2012; Lang & Dickerson, 2017b), and breast cancer survivors may have used the same strategy to complete the lift with this standardized load. BC+ appear to have adjusted task strategy in other ways to compensate for humeral range of motion challenges in the repetitive reaching task; during this task many breast cancer survivors tossed the marble into the second bowl from a slight distance, instead of reaching or twisting to place the marble.

Humeral/torso trade-offs were absent in other tasks. Overall, it appears that global kinematics of breast cancer survivors beyond the acute phase of recovery (i.e. beyond 6 months post-mastectomy) from treatment are not affected by humeral range of motion deficits in functional tasks.

Impingement pain was represented almost equally for right and left sides of BC+, with nine right shoulders and eight left shoulders with at least one positive on the impingement tests. All of the shoulders with impingement pain, except one, corresponded to sides that had mastectomies: of breast cancer survivors with bilateral mastectomies, 3/10 had impingement pain on both sides. Fifteen breast cancer survivors had unilateral mastectomies, and 8 of those had impingement pain on the side treated with surgery. One breast cancer survivor with a unilateral mastectomy had pain on both sides, while one participant who had undergone bilateral mastectomy only had pain on the left side. Still, kinematic alterations often only presented on right shoulders with impingement pain. Because all breast cancer survivors and all but two controls were right-hand dominant, and differences in scapular kinematics between dominant and non-dominant sides at rest and in arm elevation are common (Morais & Pascoal, 2013; Oyama et al., 2008; Schwartz et al., 2014), dominance appears to play an important role in understanding alterations due to pain or injury development. However, task performance with the dominant hand is generally more



precise, faster, and less variable (Elliott et al., 1993; Peters, 1998; Todor, Kyprie, & Price, 1982), so the kinematic variability when using the non-dominant side could have obscured differences between groups on the left side (Figure 4.4).



**Figure 4.4: Variance (standard deviation squared) of upward rotation of the right and left scapulae during the fifteen overhead lift cycles for control participants and BC+. Left side for both groups demonstrated higher variance than the right side throughout each lift cycle.**

The kinematic differences present during performance of these functional tasks are important because movements and tasks similar to these are performed regularly in daily life. Whether at home or at work, tasks or motions that require reaching to the side, reaching up, or lifting something overhead are frequent and the experimental tasks were chosen to replicate and test ability to perform these functions (Reneman et al., 2005). No kinematic differences occurred in the least strenuous tasks (i.e. the fingertip and hand and forearm dexterities), suggesting that

tasks with similar repetitive and fine motions (Reneman et al., 2005), such as office work, are lower risk for future shoulder injury development. However, tasks that require overhead motions or movement near the extremes of humeral range of motion resulted in compensations that, when performed repetitively, may increase the likelihood of injury (Cohen & Williams, 1998).

Therefore, if these types of movements are a job requirement, they should be meticulously monitored and evaluated. The focus of return-to-work specific rehabilitation should be to improve performance and movement strategies during these tasks, or conversely, modify the task at work to better meet the abilities of each breast cancer survivor. While more research is needed to determine the best approach to rehabilitation and return-to-work for prevention and treatment of rotator cuff disease in breast cancer survivors after surgery, current common strategies such as increasing strength, endurance, and range of motion through physiotherapy (McNeely et al., 2010) are likely to be beneficial until a more specified treatment approach can be determined.

In addition to the kinematic alterations associated with impingement pain, the BC+ group also consistently had poorer performance capacity than controls. Even for tasks in which there were no movement compensations, performance was comprised: slower times in repetitive reaching and hand and forearm dexterity tasks, fewer pins in the fingertip dexterity task, and shorter duration in the overhead work (Table 3). Traditionally, return-to-work evaluations are focused on capacity outcomes (Soer et al., 2009) and the performance scores from this group would suggest that, even for the tasks without potentially harmful movement strategies, BC+ would not be ready to return-to-work even though they were, on average, almost six years from surgery. While the kinematic compensations are vital to monitor for injury prevention, physical capacity is also important to rehabilitate and monitor for many years post-surgery, as diminished capacity indicates an inability to return-to-work.

Some study-specific limitations influence both the results and their interpretation. First, sample characteristics may have complicated results; a larger group, with more left- hand dominant breast cancer survivors and controls, could confirm potentially important differences and trends in kinematic data. Second, the extent of axillary surgery of participating breast cancer survivors is not known, which could be another factor in determining kinematic alterations and functional deficits (Crane-Okada et al., 2008; Wennman-Larsen et al., 2013). There is also no available data of the preoperative rotator cuff disease status for each participant; it cannot be said with certainty that impingement pain was only present after surgery. Additionally, the implications of kinematic differences are complex. While decreases in upward rotation are consistently associated with rotator cuff disease, it is not clear if this alteration truly influences the acromiohumeral proximities (Lawrence, Braman, & Ludewig, 2019). A long-term follow-up of breast cancer survivors would provide more insight into whether these kinematics are a cause or symptom of rotator cuff disease progression. Finally, the mechanism for kinematic alterations is not clear from this dataset. Investigating muscle strategy differences could highlight causes for differences and further guide rehabilitation.

#### **4.6 Conclusions**

The presence of impingement pain strongly influences work-related functional task performance in breast cancer survivors past the acute phase of recovery. Performance capacity is reduced and kinematics reflect potentially harmful movement strategies that could contribute to further rotator cuff disease development and should be monitored throughout rehabilitation. In particular, scapular upward rotation decrements should be evaluated; appropriate treatment options may include scapular positioning training, but this strategy needs further testing.

## **TRANSITION BETWEEN CHAPTER 4 AND CHAPTER 5**

The third chapter (manuscript #2) defined upper limb kinematics of breast cancer survivors during a return-to-work evaluation protocol. Biomechanical evidence identified a possible relationship between breast cancer treatment and rotator cuff disorders and datasets were developed for controls and cancer survivors.

While kinematic alterations provide insight into injury risk, elucidating mechanisms for those movement compensations would allow for an improved understanding both of the changes in musculoskeletal system of the shoulder after mastectomy and improved recommendations for treatment. The next chapter will estimate individual muscle forces during functional task performances; doing so will not only define muscle strategies during novel task performance for breast cancer survivors and controls, but also directly connect differences in muscle predictions to differences in kinematics, providing robust evidence for clinical recommendations.

## **CHAPTER 5: ESTIMATING MUSCLE FORCES FOR BREAST CANCER SURVIVORS DURING FUNCTIONAL TASKS**

Angelica E. Lang<sup>1\*</sup>, Soo Y. Kim<sup>2</sup>, Stephan Milosavljevic<sup>2</sup>, & Clark R. Dickerson<sup>3</sup>

<sup>1</sup> Department of Health Sciences, College of Medicine, University of Saskatchewan, Canada

<sup>2</sup> School of Rehabilitation Science, College of Medicine, University of Saskatchewan, Canada

<sup>3</sup> Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, Canada

### **Contribution:**

Angelica Lang was a primary contributor to the study conception and design. She led and completed all requirements for data collection. A previously developed model is used in this study, but Angelica was responsible for the model amendments necessary for this study. She was also the primary author of the manuscript.

### **Publishing Status**

This manuscript has been submitted to the *Journal of Applied Biomechanics*.

## 5.1 Abstract

**Introduction:** Breast cancer survivors have known scapular kinematic alterations that may be related to the development of secondary morbidities. A measure of muscle activation would help understand the mechanisms behind potential harmful kinematics. The purpose of this study was to determine if muscle force predictions were different between breast cancer survivors and non-cancer controls during functional task performance, with a secondary objective to confirm the ability of the chosen model to predict forces with these parameters.

**Methods:** Shoulder muscle forces during six functional tasks were predicted for 25 breast cancer survivors (divided by impingement pain) and 25 controls using a modified version of the Shoulder Loading Analysis Module (SLAM). The differences between maximum predicted forces and maximum EMG were compared with repeated-measures ANOVAs ( $p < 0.05$ ) to evaluate the success of the model predictions. Maximum forces for each muscle were then calculated and one-way ANOVAs ( $p < 0.05$ ) were used to identify group differences.

**Results:** Differences between force predictions and EMG ranged from 7.3%-31.6%, but were within the range of previously accepted differences. Impingement related pain in breast cancer survivors was associated with increased force predictions of select shoulder muscles. Both pectoralis major heads, upper trapezius, and supraspinatus forces were consistently higher in the breast cancer survivor with pain group, while the rhomboid major and minor, intermediate trapezius, posterior deltoid, subscapularis, serratus anterior, long head of the biceps and brachioradialis forces were also higher in individual tasks.

**Conclusions:** Impingement related pain in breast cancer survivors is associated with increased force of select shoulder muscles, such as the upper trapezius, supraspinatus, and pectoralis major.

These force prediction differences are also associated with potentially harmful kinematic strategies, providing a basis for potential rehabilitation strategies.

## 5.2 Introduction

Arm and shoulder problems are common following breast cancer treatment. In the Canadian province of Saskatchewan, up to 83% of survivors report at least one upper limb limitation within five years of treatment (Lang et al., n.d.), and this dysfunction is a frequent occurrence for breast cancer survivors globally (De Groef et al., 2016; C. H. Lee, Chung, Kim, & Yang, 2019; Verbelen, Tjalma, Meirte, & Gebruers, 2019). Breast cancer survivors are also more likely to experience secondary shoulder morbidities in the years following treatment, such as rotator cuff disorders or adhesive capsulitis (Ebaugh et al., 2011; Yang et al., 2010). The etiology of such secondary dysfunction is not well understood, which has implications for determining effective treatment, rehabilitation, and return-to-work strategies for breast cancer survivors.

Rotator cuff disease, in particular, has been strongly associated with breast cancer treatment. Previous work reported that almost 50% of a sample of breast cancer survivors presented with impingement-related pain, as determined by a positive on at least one out of three common impingement special tests (Lang, Dickerson, Kim, Stobart, & Milosavljevic, 2019). This group exhibited shoulder kinematics that are consistent with those who have rotator cuff impingement diagnosis (Lang, Dickerson, et al., 2019; Ludewig & Reynolds, 2009). However, a measure of muscle activation is required in order to better understand the mechanisms causing kinematic alterations and to identify contributing muscles that may benefit from focused rehabilitation (Campbell et al., 2014; Hotta, Santos, McQuade, & de Oliveira, 2018).

Musculoskeletal (MSK) modelling allows for estimation of muscle forces and loading strategies for more muscles than can be feasibly measured. For a pathological population, the goal of modelling is often to determine how structural differences caused by injury or disorder affect function. As most MSK models are created and used for healthy groups with no limitations, they



often require modification for clinical applications. These types of modifications may include decreasing the capability of muscle (Chopp-Hurley et al., 2016), altering lines of action, or even removing muscles from the model entirely (Lemieux et al., 2012). With regards to breast cancer, the pectoralis major muscle in survivors has reduced capability following surgery (Dalberg et al., 2010; de Haan et al., 2007; Shamley et al., 2007). As such, biomechanical models developed on a healthy population could have the force capacity of the pectoralis major (both sternal and clavicular heads) adjusted to reflect these limitations.

When modelling pathological populations, kinematics are also an important consideration. However, representation of the scapula in MSK models has been a source of difficulty for biomechanists. Historically, measurement of the scapula has not always been feasible, so scapulohumeral rhythms, in the form of regression models based on humeral elevation angle, have been used as a solution to determine scapular orientation (de Groot & Brand, 2001; Dickerson et al., 2007; Grewal & Dickerson, 2013). A shoulder rhythm developed from a healthy population may not capture the potentially harmful kinematic alterations present in a pathological population, such as reductions in upward rotation measured in breast cancer survivors (Lang, Dickerson, et al., 2019). Because muscle force estimates are sensitive to small changes in humeral and scapular posture (W. Wu, Lee, & Ackland, 2017), inputs that are as accurate as feasibly possible are needed to capture muscle force pattern differences that are associated with pathological shoulder motion, particularly due to the known altered scapular orientations in the current sample.

The goal of this study was, first, to explore the ability of the Shoulder Loading Analysis Modules (SLAM) to predict muscle forces in these functional tasks utilising measured scapular orientations as input with adjusted pectoralis capacity, and second, to determine the differences

in muscle force predictions between breast cancer survivors (with and without impingement pain), and non-cancer controls during arm-focused functional task performance. This novel research intends to clarify the mechanisms for kinematic differences between the groups, providing previously unknown insight into shoulder function in the population.

## **5.3 Methods**

### ***5.3.1 Participants***

Twenty-five breast cancer survivors ([mean (SD)] age(years) = 51.6 (7.0), height (m) = 1.62 (0.08), weight (kg) = 68.7 (11.8)) and twenty-five non-cancer controls ([mean (SD)] age(years) = 54.0 (5.2), height (m) = 1.61 (0.06), weight (kg) = 72.5 (15.3)) participated. All breast cancer survivors had undergone either unilateral or bilateral mastectomy at least 6 months prior to participation, with no breast reconstructive surgery. The control group were free from upper limb impairments. The study protocol was approved by the university research ethics board and all participants provided written informed consent prior to the experiment.

### ***5.3.2 Procedures***

Prior to task performance, each participant completed clinical questionnaires and was evaluated with three clinical tests for impingement: Neers' Impingement test, Hawkins-Kennedy Impingement, and empty can test (Calis, 2000; Moen et al., 2010). Reflective markers for motion capture (Vicon Motion Systems, Oxford, UK) and sensors for electromyography (EMG) (Delsys Trigno™ Wireless EMG sensors (Delsys, Inc)) were placed on each participant's right upper body. Only the right side was analyzed in this study for two reasons: 1) SLAM is a model of the right upper limb, and 2) kinematic differences were only present on the right side in this sample. Individual markers and rigid clusters were affixed to the torso and arm at anatomical points

based on International Society of Biomechanics recommendations (G. Wu et al., 2005). An acromial marker cluster (AMC) was used to track the scapula (Lang, Kim, et al., 2019; van Andel et al., 2009). EMG sensors were placed over the muscle belly of the pectoralis major clavicular and sternal heads, supraspinatus, upper trapezius, posterior head of the deltoid and the infraspinatus (Brookham et al., 2018b; Cram & Kasman, 1998). Maximum voluntary contractions (MVC) were performed to elicit highest possible activity from each muscle before beginning the experimental protocol. The motion capture space was sampled at 50 Hz and EMG channels were sampled at 2000 Hz using a synchronized system.

Six work-related functional tasks made up the experimental protocol: overhead reach, repetitive reach, fingertip dexterity, hand and forearm dexterity, overhead lift, and overhead work. The overhead reach involved reaching with one hand from a low shelf to high shelf, while seated, with both a 1kg load and unloaded. The repetitive reach required participants to move 30 marbles from one bowl to another as quickly as possible with one hand, while seated. Bowls were placed at the wingspan of each participant. For the fingertip dexterity and hand and forearm dexterity tasks, the Purdue Pegboard (Lafayette Instrument, 2002) and Minnesota Manual Dexterity Test (Lafayette Instrument, 1998) were used, respectively. For the overhead lift, participants were required to lift an 8 kg load from a low shelf to a high shelf with both hands, while standing. This was repeated 3 sets of 5 repetitions. Finally, the overhead work task required participants to manipulate nuts and bolts at forehead level for as long as possible, while wearing 1 kg wrist weights. Together, these tasks represent the general procedures of a clinical, return-to-work upper limb evaluation and test several aspects of movement and function (Reneman et al., 2005). For a more detailed description of each individual task, please see Lang et al. (2019).

### **5.3.3 Data analysis**

Kinematic and EMG data were processed with custom Matlab<sup>TM</sup> programs. Kinematic data were filtered with a low-pass, zero-lag, fourth-order Butterworth filter with a 6 Hz cut-off (Winter, 2009) and converted to joint centres for input into the MSK model. EMG data were initially high-pass filtered at 30 Hz to remove heart rate artifact (Drake & Callaghan, 2006) and then linear enveloped with a low-pass second order single-pass Butterworth filter with a 2.5 Hz cut off (Chopp-Hurley et al., 2016). Each linear enveloped signal was normalized to the peak MVC value for each muscle. Due to repetitive nature of each task, cycles were identified for each repetition and trial using the right second metacarpal marker and equipment reference markers (Lang, Dickerson, et al., 2019). Both kinematic and EMG data were separated in cycles and ensemble averaged. For the overhead work, the last 30 seconds of work was extracted and joint centre locations were averaged for input into the model.

SLAM was the shoulder MSK model used in this study (Dickerson et al., 2007; Dickerson, Hughes, & Chaffin, 2008). The model uses an optimization approach with the objective function to minimize the sum of cubed muscle stresses to address the problem of redundancy. The model takes motion files, anthropometric data, and task data as inputs for 3 separate modules: shoulder geometry constructor, external dynamic moment calculator, and internal muscle force estimator (Dickerson et al., 2007). The shoulder geometry module consists of five rigid segments (scapula, clavicle, humerus, torso, and radial/ulnar forearm link), four joints (sternoclavicular, acromioclavicular, glenohumeral, and elbow), and 23 muscles modeled as 38 separate elements (Dul et al., 1984; Grewal & Dickerson, 2013; Hogfors, Sigholm, & Herberts, 1987). The muscle wrapping techniques include spherical and cylindrical wrapping to define muscle lines of action (Dickerson et al., 2007). Muscle forces are bound by a minimum of zero and a maximum derived

from muscle-specific physiological cross-sectional areas (PCSA). Predicted estimated muscle forces were normalized to maximum capacity (Dickerson et al., 2007; Hogfors et al., 1987). A more detailed explanation of the SLAM model exists in Dickerson et al. (2007; 2008).

Two modifications were made to SLAM for this project. First, the pectoralis capacity was decreased by 50% for the breast cancer survivor group (Chopp-Hurley et al., 2016). Second, the geometry module was adjusted to receive measured scapula orientation as input, replacing the scapulohumeral rhythm calculation. Twenty-two out of 1,006 total trials included scapular orientations that were incompatible with the model, likely due to segment covariance, so these trials were excluded from the analysis. All 22 trials were overhead reach and lift trials, which are outside the original design space of SLAM. Finally, 28 trials had frames where the model was not able to converge on a minimum solution, likely due to uniform assumptions regarding muscle capabilities across persons. If the number of frames was five or less (10 times), linear interpolation was used to fill those gaps (Howarth & Callaghan, 2012). If the number of frames with non-convergence was greater than five, trials were excluded from the analysis, totaling 18. A total of 963 trials were analyzed. Since repetitions of the same task were averaged within participant, each task is represented for each participant, with the exception of 5 participant/task combinations.

#### ***5.3.4 Statistical Analysis***

To examine the model's ability to estimate muscle forces during these tasks, force estimates were compared to empirically measured EMG. The differences between the maximum magnitudes of the muscle force estimations (% of maximum muscle capacity) and muscle activation (% of MVC) were calculated and compared by task and pectoralis capacity adjustment (Chopp-Hurley et al., 2016). A repeated measures ANOVA was used to test the effects of task on

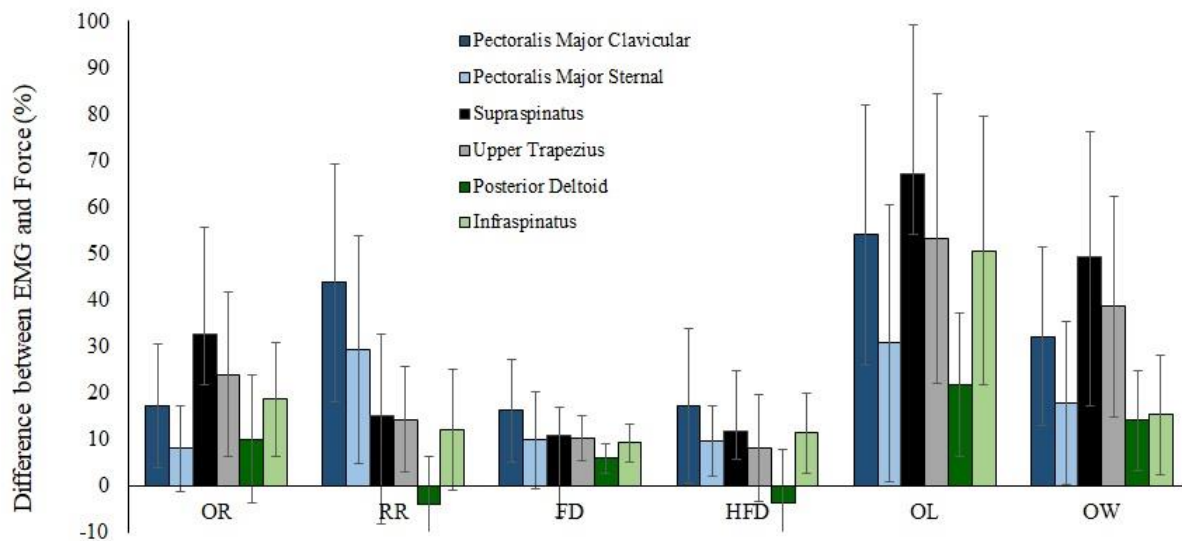
magnitude of the differences for each muscle for the control group, while a multivariate repeated measures ANOVA was used to evaluate the effect of task and pectoralis capacity on the magnitude of differences of each muscle for the breast cancer group. Main and interaction effects were analyzed at 5% significance level. A concordance analysis was also performed to assess the model's ability to predict which muscles were active or inactive (Dickerson et al., 2008). The muscles were considered 'on' for a given trial if any EMG value was over 5% of maximum MVC, or if any force estimate was over 5% of the maximum force producing capacity. If the EMG and force predictions both indicate presence or absence of muscle activity, concordance existed, but if the metrics disagreed, discordance existed. To determine overall concordance, a concordance ratio was calculated by dividing the number of trials that were concordant by the number that were discordant, for each participant. If the ratio was greater than 1, the muscle was considered concordant, but if the ratio was less than 1, the muscle was discordant.

To compare the muscle force estimation values between groups, maximum values were calculated for each muscle and task. Breast cancer survivors were divided post-hoc based on results of the clinical impingement tests. A positive on any impingement test warranted inclusion into the breast cancer survivor 'with pain' group, while those without any positives were placed in the breast cancer survivors 'without pain' group. To determine differences in muscle force predictions of the two breast cancer survivor groups (pain and no pain) and control group, one-way ANOVAs were run for each task and muscle, with muscle force as the dependent variable and group as independent variable.

## 5.4 Results

### 5.4.1 Comparison to EMG

Predicted muscle forces generally underestimated empirically measured activity. The average difference for each muscle, across all comparisons, was 30.0 %, 17.5 %, 31.6 %, 24.6 %, 7.3 %, and 19.5 % for the pectoralis major clavicular head, pectoralis major sternal head, supraspinatus, upper trapezius, posterior deltoid, and infraspinatus, respectively. The largest differences occurred during the overhead lift and overhead work, and the supraspinatus force estimates were the most different from EMG maximums (Figure 5.1). When pectoralis major muscle capabilities were adjusted for the breast cancer survivors, only the two pectoralis muscles were affected: the difference between force estimates and EMG activity decreased by up to 6.3% (mean = 1.63%) ( $p < .001$ ,  $\eta^2 = .208-.403$ ).



**Figure 5.1: Mean differences between estimated muscle forces and measured muscle activity for each task and muscle, averaged across groups. Positive differences indicate that model predictions were lower than measured EMG. Large differences were present in the overhead lift and work comparisons. Functional tasks are along the x-axis: OR = overhead reach; RR = repetitive reach; FD = fingertip dexterity; HFD = hand and forearm dexterity; OL = overhead lift; OW = overhead work.**

Adjusting pectoralis capacity also improved concordance of the pectoralis muscles for the breast cancer survivor group, but did not affect the other muscles. The pectoralis clavicular head concordance ratio increased from 0.388 to 0.572, while the sternal head went from 0.710 to 1.344. Across all tasks, for both groups, the upper trapezius, posterior deltoid, and infraspinatus were concordant (Table 5.1).

**Table 5.1: Overall concordance ratios for each muscle by group. The breast cancer group ratios are based on muscle force estimates from the modified SLAM.**

	Pectoralis clavicular	Pectoralis sternal	Supraspinatus	Upper Trapezius	Posterior Deltoid	Infraspinatus
<b>Control</b>	0.54	0.78	0.52	2.49	2.29	3.77
<b>Breast cancer survivors</b>	0.57	1.34	0.76	1.65	2.95	3.18

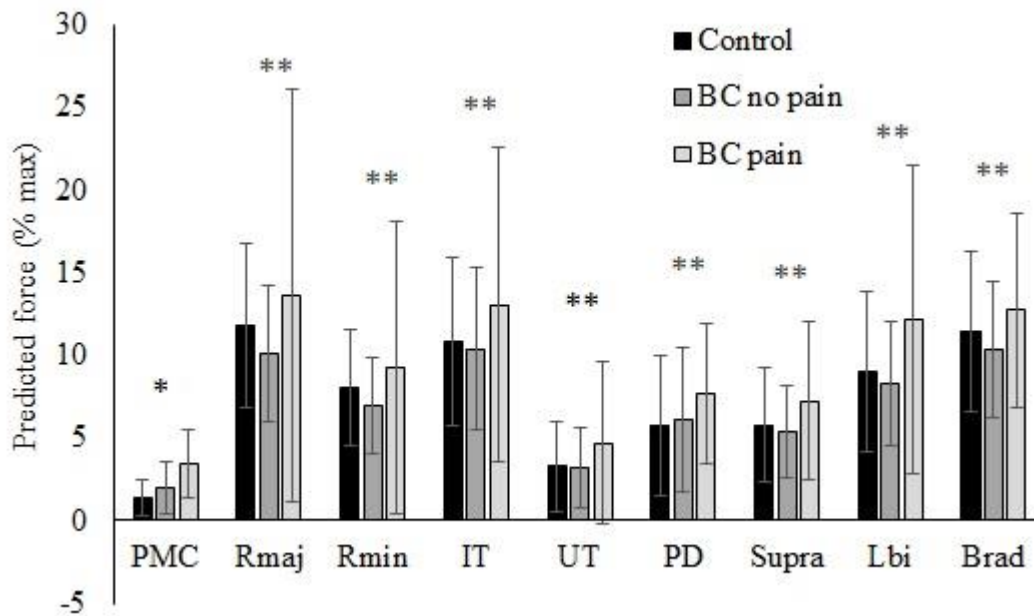
#### **5.4.2 Group Comparisons**

Muscle force predictions for the breast cancer group with pain were higher than controls and breast cancer group without pain. Of the 38 muscle elements estimated, 4 were consistently higher in the breast cancer survivor with pain group ( $p = .000 - 0.020$ ,  $\eta^2 = .008 - .069$ ) over all tasks: both pectoralis major heads, upper trapezius, and supraspinatus.

When examining muscle force differences by task, breast cancer survivors with pain generally had higher predicted forces. During the overhead reach, pectoralis major clavicular head, rhomboid major and minor, intermediate and upper trapezius, posterior deltoid, supraspinatus, long head of the biceps and brachoradialis had higher predicted forces than the other groups ( $p = .000-.039$ ,  $\eta^2 = .025-.206$ ) (Figure 5.3). The overhead lift had similar results; the upper trapezius, supraspinatus, and posterior deltoid were higher in the pain group than controls (difference = 2.8



– 5.2%,  $p = <.001-.028$ ,  $\eta^2 = .038-.103$ ). The force estimates of both heads of the pectoralis major and the lower portion of the subscapularis were also higher in both breast cancer survivor groups during the overhead lift (difference = 1.65 – 5.6%,  $p = <.001-.028$ ,  $\eta^2 = .057-.160$ ). Finally, results from the repetitive reaching task concurred with the results from the main effect of group, with the exception of the lower element of the serratus anterior, which was higher in the control group than both breast cancer groups (difference = 3.7%,  $p = .008$ ,  $\eta^2 = .128$ ), and lower subscapularis, which was higher in the breast cancer with pain group (difference = 2.1%,  $p = .045$ ,  $\eta^2 = .047$ ).



**Figure 5.2: Peak predicted forces of muscles that were different between groups during the overhead reach.** PMC = pectoralis major clavicular head; RMAJ = rhomboid major; RMIN = rhomboid minor; IT = intermediate trapezius; UT = upper trapezius; PD = posterior deltoid; SUPRA = supraspinatus; LBI = lower biceps brachii; BRAD = brachioradialis.

\* represents difference between both breast cancer groups and the control group.

\*\* represents difference between breast cancer survivors with pain and breast cancer survivors without pain or controls.

## 5.5 Discussion

The model predicted muscular activity with mixed results, using experimental EMG as a comparison. With the modification of adding measured scapular orientation to replace the scapulohumeral rhythm equation, the model executed successfully for most trials (97.8%) and identified differences in muscle force patterns between groups that coincide with reported kinematic alterations.

Agreement between force estimates and measured EMG varied with task and muscle. The overall averages of the differences approximated values reported in Chopp-Hurley et al. (2016) (13.5 – 30.4%), which evaluated the model's ability to predict muscle activation summed over internal and external humeral rotator muscle groups. Concordance ratios also agreed with Dickerson (2008), demonstrating general success of the model with the current modifications and these tasks. However, when examining individual muscles, agreement for the pectoralis major clavicular head and supraspinatus is poor. The discrepancy between measures could be a function of several factors: co-contraction is not well represented in optimization models (Dickerson et al., 2007), experimental MVCs may not be accurate in this non-normative population, and EMG and muscle force are not linearly related, especially in dynamic conditions (Disselhorst-klug, Schmitz-rode, & Rau, 2009). Due to the challenging nature of these functional tasks, it can be presumed that most muscles of the shoulder were active to assist in movement and stability of the arm and shoulder (Blache, Maso, Desmoulins, Plamondon, & Begon, 2015). Therefore, co-contraction is likely responsible for the large differences between EMG and force estimates, especially for the tasks with external loads. Inaccurate MVCs are also a known limitation of EMG, particularly when working with a compromised population, due to physical limitations or pain avoidance (Lindstroem, Graven-Nielsen, & Falla, 2012). Lower-than-true

maximum MVCs would result in overestimated muscle activity and exaggerated differences between activity and forces, but normalization of muscle effort (either EMG or force predictions) is necessary to compare the two datasets. Finally, while EMG and muscle force are considered related, it is not a direct linear relationship, meaning that a proportion of maximum EMG does not necessarily correspond to the same proportion of muscle force. Comparing to EMG is one strategy to determine model effectiveness, but due to known and accepted limitations of both EMG and MSK modelling, discrepancies between measures do not necessarily render the model outputs inaccurate; agreement within the range of previous work (Chopp-Hurley et al., 2016; Dickerson et al., 2008) suggests the utility of model predictions to provide a measure of muscle force patterns to elucidate possible muscle patterns causing kinematic alterations.

The muscle force prediction differences between groups coincide with kinematic differences. The increased upper trapezius force present in breast cancer survivors with pain is likely related to reduced upward rotation of the scapula (Phadke et al., 2009). An increase in upper trapezius force without an accompanying increase in serratus anterior or lower trapezius activity could interrupt the force couple required for appropriate upward rotation and scapulohumeral rhythm (Paine & Voight, 2013). Upper trapezius muscle activity has previously been reported as increased in both breast cancer survivor and rotator cuff disease populations (Brookham et al., 2018b; Galiano-Castillo et al., 2011), indicating the importance of this muscle for scapular kinematics. Overactive upper trapezius, combined with tightness, fibrosis, and other muscle damage from treatments (Kuehn et al., 2000; Leidenius et al., 2003), positions the scapula in a less desirable posture throughout task performance, indicating that preventative action or rehabilitation should be focused around the upper trapezius and surrounding muscles.

Supraspinatus and posterior deltoid force were highest in the breast cancer survivors with pain, consistent with kinematic changes. When the scapula is more downwardly rotated, movement at the glenohumeral joint must compensate, as the scapula and humerus work together to elevate the arm (Braman et al., 2009; McClure et al., 2001; Roren et al., 2017). Both the supraspinatus and posterior deltoid originate on the scapula and work as glenohumeral elevators; when the scapula is in a more downwardly rotated position, these muscles must then increase contribution during arm elevation. The increased demand on the supraspinatus, combined with the possible mechanical impingement from scapular orientation (Lang, Dickerson, et al., 2019; Michener, McClure, & Karduna, 2003; Seitz, McClure, Finucane, Boardman, & Michener, 2011), could result in overload of the tendon and contribute to the development of rotator cuff disease. It is important to note that this group of breast cancer survivors with pain were not formally diagnosed with rotator cuff disease or recruited based on pain; while these results are consistent with the expectations for a rotator cuff disease group, there is not enough clinical information to confirm a rotator cuff pathology. Despite the lack of confirmed diagnosis, these findings nonetheless provide important information that could apply to the development of rotator cuff injuries in breast cancer survivors.

Other muscle compensations from the current findings are related to the pectoralis limitations in breast cancer survivors. The consistent differences in pectoralis force predictions between both breast cancer groups and the control group are possibly a direct result of modelling choices to represent the compromised pectoralis muscle. Subscapularis muscle elements also had higher predicted forces in both groups of breast cancer survivors during the overhead and repetitive reaching tasks. Increases in subscapularis forces are a logical compensation for pectoralis limitations because they are both internal rotators (Dark, Ginn, & Halaki, 2007). These

alterations may be directly related to adjustments made to the model, but since the modelling choices were based on known pectoralis decrements in breast cancer survivors (Dalberg et al., 2010; de Haan et al., 2007; Shamley et al., 2007), it is logical that pectoralis and subscapularis muscles are working at a higher percentage of their capacity in breast cancer survivor. Higher force production in these muscles could have implications both for shoulder movement and possibility of quicker fatigue, overload, and eventual further damage.

There are many known limitations when predicting muscle forces with MSK models. As mentioned, SLAM does not explicitly include co-contraction for antagonist/accessory muscles, though a unique glenohumeral stability constraint does encourage it somewhat, and assumes consistent scaling of anthropometric factors, such as segment dimensions and muscle attachment sites (Dickerson et al., 2007). These factors could contribute to variance in force predictions. There are also considerations from the measured kinematics, particularly with the use of an AMC marker cluster. Even though its utility has been confirmed (Lang, Kim, et al., 2019), there are still inherent issues with motion capture and accepted errors with scapular measurement. However, the differences between groups persist despite these limitations, indicating their robustness and presenting meaningful insights that improve the understanding of shoulder function in healthy individuals and breast cancer survivors with mastectomies.

## **5.6 Conclusions**

Overall, these results support the use of SLAM for modelling a breast cancer survivor population, using a measured scapular orientation as input. Increases in several predicted muscle forces during functional tasks in breast cancer survivors allows for unprecedented insight into potentially harmful muscle force patterns. In particular, upper trapezius, supraspinatus, and

pectoralis major are overactive in the breast cancer survivors with pain. Future work should test potential rehabilitation methods to address these compensations.

## **TRANSITION FROM CHAPTER 5 TO CHAPTER 6**

The third and fourth chapters of this thesis collectively identified what kinematics compensatory alterations exist in breast cancer survivors and what muscle patterns may relate to these alterations. The studies focused on functional task performance, to emulate movements performed in everyday life, and particularly during work.

However, while functional tasks analyses have clear implications for return-to-work and daily living, functional tasks are seldom applied in either fundamental testing or clinical evaluations. Shoulder motion is frequently evaluated during arm elevation, in part due to the ability to standardize movements. In order to best disseminate the data from Chapters 4 and 5 to clinicians, identifying highly informative assessment methods should be investigated.

The final manuscript for this dissertation aims to determine if scapular motion during simple arm elevations can infer functional task performance. Because of the known compensations during functional tasks, evaluating differences between groups during arm elevation and then quantifying the relationship between scapular motions in the different types of movements will contribute to the goal of providing specific recommendations for effective clinical treatment and assessment of shoulder function among breast cancer survivors.

## **CHAPTER 6: EXAMINING ASSESSMENT METHODS OF SCAPULAR MOTION: IS ARM ELEVATION ENOUGH?**

Angelica E. Lang<sup>1</sup>, Stephan Milosavljevic<sup>2</sup>, Clark R. Dickerson<sup>3</sup>, Soo Y. Kim<sup>2</sup>

<sup>1</sup> Department of Health Sciences, College of Medicine, University of Saskatchewan, Canada

<sup>2</sup> School of Rehabilitation Science, College of Medicine, University of Saskatchewan, Canada

<sup>3</sup> Department of Kinesiology, Faculty of Applied Health Sciences, University of Waterloo, Canada

### **Contribution:**

Angelica Lang was a primary contributor to the study conception and design. She led and completed all participant recruitment, data collection sessions, and data analysis. She was also the primary author of the manuscript.

### **Publishing Status**

This manuscript has been submitted to *Clinical Biomechanics*.



## 6.1 Abstract

**Background:** Scapular kinematics are most often evaluated during arm elevation in both the lab and the clinic. However, while shoulder kinematic and muscle force strategy compensations exist in breast cancer survivors during functional task performance, it is not known if biomechanical differences present in functional tasks are also present in arm elevation, and vice versa. The purpose of this study was to determine if scapular kinematics during arm elevation are related to scapular kinematics during functional task performance.

**Methods:** Scapular kinematics of fifty women (25 non-cancer controls, 16 breast cancer survivors without impingement pain, and 9 breast cancer survivors with impingement pain) during arm elevation in three planes and three functional tasks were measured. Scapular upward rotation and scapulohumeral rhythm (SHR) at select arm elevations were calculated. Between-group differences of upward rotation during arm elevation were evaluated with one-way ANOVAs ( $p < 0.05$ ). The association of upward rotation angle and SHR during arm elevation and functional tasks was tested with Pearson correlations ( $p < 0.05$ ).

**Results:** Scapular upward rotation was reduced for the breast cancer survivors with pain at lower levels of arm elevation in each plane by up to  $7.1^\circ$ . This is inconsistent with functional task results, in which upward rotation decrements occurred at higher levels of arm elevation. Upward rotation angles during arm elevation had an overall moderate to strong relationship to angles during functional tasks, but SHR between the two types of motions only had an overall weak-to-moderate relationship.

**Conclusions:** Arm elevation during sagittal plane elevation demonstrated scapular upward rotation that was most closely associated to upward rotation during functional task performance.

However, inconsistent relationships suggests that clinical evaluations should adopt basic functional movements for scapular motion assessment to complement simple arm elevations.

## 6.2 Introduction

Shoulder pathologies are associated with altered upper limb biomechanics. Indeed, certain kinematic compensations could contribute to some overuse injuries; for instance, decreased upward rotation of the scapula, in particular, is associated with shoulder impingement (Keshavarz, Bashardoust Tajali, Mir, & Ashrafi, 2017; Ludewig & Reynolds, 2009). However, the kinematic compensations that are considered to be associated with injuries are most often measured during open chain, unloaded arm elevations (Keshavarz et al., 2017), which may not represent the scapular kinematics during the functional movements that are performed repetitively either during work tasks or activities of daily living.

Many studies that have analyzed scapular kinematics do so for arm elevation in a single plane. This is a common strategy for scapular kinematic assessment because of ease of performance, repeatability, and applicability to clinical practice (McFarland, Garzon-Muvdi, Jia, Desai, & Petersen, 2010). With regards to shoulder pathologies, research studies also most often focus on motion during elevation in one or two planes (Borstad & Ludewig, 2002; Borstad & Szucs, 2012; F. Fayad et al., 2006; Ludewig & Reynolds, 2009; McClure, Tate, Kareha, Irwin, & Zlupko, 2009; Yamaguchi et al., 2000). This approach is practical because shoulder biomechanics is still a relatively new area of research, and scapular motion can be difficult to assess depending on available equipment and expertise.

Previous research by published by this group reported scapular kinematic differences present in breast cancer survivors during overhead reaching and lifting (Lang, Dickerson, Kim, Stobart, & Milosavljevic, 2019). The breast cancer survivors with any impingement-related pain had reduced scapular upward rotation during functional task performance. Other investigations have also noted a similar relationship of pain and disability with altered scapular motion during

reaching in breast cancer survivors (Spinelli, Silfies, Jacobs, Brooks, & Ebaugh, 2016), highlighting the importance of scapular motion to function. Still, there is no evidence to confirm that the scapula moves in the same pattern for both simple arm elevation and functional tasks, meaning that alterations that exist in functional tasks may not also be present in arm elevations, bringing into question the appropriateness of elevation-based shoulder evaluation.

Given that motion assessment during arm elevation is routine in clinical practice, and that there are inherent difficulties in evaluating the scapula during functional tasks, an enhanced understanding of the correlation between scapular motion during basic arm elevation and scapular motion during a range of functional tasks could improve understanding of shoulder function. Quantifying this relationship will highlight the utility of identifying alterations during basic motion to infer daily functional performance (i.e. does altered scapular motion in arm elevation translate to altered motion in functional tasks, and vice versa). For that reason, the purpose of this study is twofold: first, to test for differences in scapular upward rotation between breast cancer survivors (with and without impingement pain) and non-cancer controls during arm elevation and, second, to determine the relationship of scapular upward rotation during arm elevation to scapular upward rotation during functional tasks for the same three groups. This approach attempts to answer the question: “Is evaluation of scapular motion during arm elevation enough?” It is hypothesized that upward scapular rotation at peak arm elevation will be lower in breast cancer survivors with pain. Further, it is expected that scapular kinematics during elevation in the scapular and sagittal plane will be moderately associated with kinematics in functional tasks and that the measures will be more highly correlated in the control group.

## **6.3 Methods**

### ***6.3.1 Participants***

Twenty-five breast cancer survivors and twenty-five age-group matched controls were recruited for this observational case-control study (Table 6.1). Based on previous research (Lang, Dickerson, et al., 2019), breast cancer survivors were divided into two groups based on impingement pain tests on the right arm (only the right arm was analyzed in this study): breast cancer survivors with no pain and breast cancer survivors with pain. To be eligible, breast cancer survivors were required to have had a mastectomy at least 6 months prior to participation and controls had to be free from any upper limb pain or impairments. Other exclusion criteria included being outside the age range of 35 to 65, inability to raise arms overhead, previous shoulder surgery other than the mastectomy, and any allergy to skin adhesives. The study protocol was approved by the university research ethics board and all participants provided written informed consent.

**Table 6.1: Demographic information and clinically relevant variables for breast cancer survivors and controls. The right side was analyzed in this study, so the breast cancer groups are split by pain in the right arm.**

	<b>Control (n = 25) Mean (SD)</b>	<b>Breast cancer no pain (n = 16) Mean (SD)</b>	<b>Breast cancer pain (n = 9) Mean (SD)</b>
<b>Age (yrs)</b>	51.6 (7.0)	53.1 (5.5)	55.6 (4.4)
<b>Height (m)</b>	1.62 (0.08)	1.61 (0.06)	1.60 (0.04)
<b>Weight (kg)</b>	68.7 (11.8)	73.6 (16.1)	70.0 (14.5)
<b>Dominance (R/L)</b>	23/2	16/0	9/0
<b>QuickDASH (/100)</b>	4.7 (6.3)	16.2 (12.4)*	17.7 (6.8)*
<b>Time since surgery (months)</b>	0	50.9 (45.7)	67.3 (34.7)
<b>Elevation range of motion (°)</b>	150.4 (12.3)	151.3 (12.8)	145.8 (17.0)
<b>Extension range of motion (°)</b>	48.6 (15.3)	35.3 (13.0)*	37.6 (17.0)
<b>Lymph node removal (Right side)</b>	-	8/16	9/9
<b>Chemotherapy</b>	-	13/16	6/9
<b>Radiation (Right side)</b>	-	5/16	5/9

\*denotes significant difference compared to control group

### **6.3.2 Experimental Procedures**

Each individual completed the Quick Disability of the Arm, Shoulder, and Hand Questionnaire (QuickDASH) and the Physical Activity Readiness Questionnaire upon arrival to the lab.

Participants were next evaluated with three impingement pain tests: Neer's sign, Hawkins-Kennedy, and the empty can (Calis, 2000; Moen et al., 2010). A positive result on any one of the tests resulted in exclusion from the control group, while at least one positive among breast cancer survivors resulted in placement into the breast cancer survivors with pain group.

Reflective markers and rigid marker clusters were affixed to the skin over bony landmarks of the torso, scapulae, and humeri based on International Society of Biomechanics recommendations (G. Wu et al., 2005). Scapula movements were tracked with an acromial marker cluster (AMC)

and anatomical points were located with a digitizer via a double calibration method, using postures at neutral and maximum arm elevation (Lang, Kim, et al., 2019). A marker at the distal end of the second metacarpal of the hand was also used for cycle definition. Motion was tracked with 10 VICON MX20 cameras (Vicon Motion Systems, Oxford, UK) positioned around the collection space. Marker position was sampled at 50 Hz.

After static calibrations, participants performed a total of nine dynamic arm elevations: three elevations in each of the frontal, scapular, and sagittal planes on the right side. Elevations were guided by a rigid pole placed in the current plane of elevation (Maclean et al., 2014) (Figure 6.1). Elevation order was block randomized by side and plane: all three repetitions for each side and plane combination were performed once the pole was adjusted to the desired position, with a pause between each elevation. Participants were instructed to raise their arm as high as possible and then lower to the starting position at a comfortable pace.

Data from three functional tasks were also included in this analysis: overhead reach, overhead lift, and fingertip dexterity. These tasks are a part of a larger return-to-work upper limb evaluation protocol (Lang, Dickerson, et al., 2019; Reneman et al., 2005) and were selected based on the results of Lang et al (2019), which evaluated kinematic differences between these three groups in the full set of tasks. The two overhead tasks were chosen because differences in scapular orientation were present between groups in these tasks. Scapular kinematics were not different between groups for the fingertip dexterity, repetitive reach, or hand and forearm dexterity (all tasks within the larger return-to-work protocol), and they were all performed within a similar range of humeral elevation, so the fingertip dexterity task was chosen to represent this set of reaching and dexterity tasks.



**Figure 6.1: Arm elevation in the sagittal plane guided by a rigid pole.**

### ***6.3.3 Data analysis***

Motion capture data were used to calculate right humeral and scapular angles. All raw kinematic data were filtered with a low pass zero-lag fourth order Butterworth filter with a 6 Hz cutoff (Winter, 2009) and local coordinate systems for each segment were calculated (G. Wu et al., 2005). The glenohumeral joint was calculated as 60 mm below the acromion caudally along the long axis of the torso (Nussbaum & Zhang, 2000) for humeral coordinate system calculations.



Humeral elevation was calculated as the angle between the long axes of the torso and humerus. Scapular angles were calculated using a joint coordinate system to describe rotations in clinically meaningful terms: internal/external rotation (around the Y axis), upward/downward rotation (around the X axis), and anterior/posterior tilt (around the Z axis). Upward/downward rotation was adjusted so upward rotation was positive.

The raising portion of each arm elevation was analyzed. Each cycle was defined using the hand marker: a cycle began when the hand marker moved upward 10mm and ended at the hand marker's highest position. Scapular angles at 30°, 60°, 90°, 120° and maximum humeral elevation were then extracted for analysis for each trial.

During functional tasks, movement cycles were defined with equipment reference markers and the hand marker. For the overhead reach and lift, upward movement was defined as the time during which the hand and load moved from the low shelf to the high shelf. For the dexterity tasks, a cycle was defined as when the hand moved from the starting position, to the location of the pins, and back. Scapular upward rotation angles were extracted at 60°, 90°, and maximum humeral elevation during each cycle of the overhead reach and overhead lift, as well as upward rotation at the maximum and minimum humeral elevation angles during each cycle of the fingertip dexterity task (Table 6.2).

Scapulo-humeral rhythm (SHR) was derived for each cycle of the elevations and functional tasks. SHR is calculated by dividing the change in glenohumeral elevation (derived by subtracting the change in scapular upward rotation from the change in humerothoracic elevation) over the change in scapular upward rotation for each designated range ( $[\Delta H - \Delta S] / \Delta S$ ) (Hosseinimehr, Anbarian, Norasteh, Fardmal, & Khosravi, 2015; S. Lee, Yang, Kim, & Choy,

2013; Matsuki et al., 2011). SHR across five ranges was extracted for arm elevations: minimum to 30°, 30° to 60°, 60° to 90°, 90° to 120°, and 120° to maximum humeral elevation. For the overhead reach and overhead lift, SHR was calculated for minimum to 60°, 60° to 90°, and 90° to maximum humeral elevation ranges. For the fingertip dexterity, SHR was calculated from minimum to maximum humeral elevation angle (Table 6.2).

**Table 6.2: Summary of the humeral elevation levels and ranges that were used for scapular upward rotation angle extraction or SHR calculation.**

Humeral elevations for angle extraction			Humeral ranges for SHR calculation			
Arm Elevations	Overhead Reach and Lift	Fingertip Dexterity	Arm Elevations	Overhead Reach and Lift	Fingertip Dexterity	
30	60	Min	Min - 30	Min - 60	Min - Max	
60			30 - 60			
90	90	Max	60 - 90	60 - 90		
120	Max		90- 120	90 - Max		
Max			120 -Max			

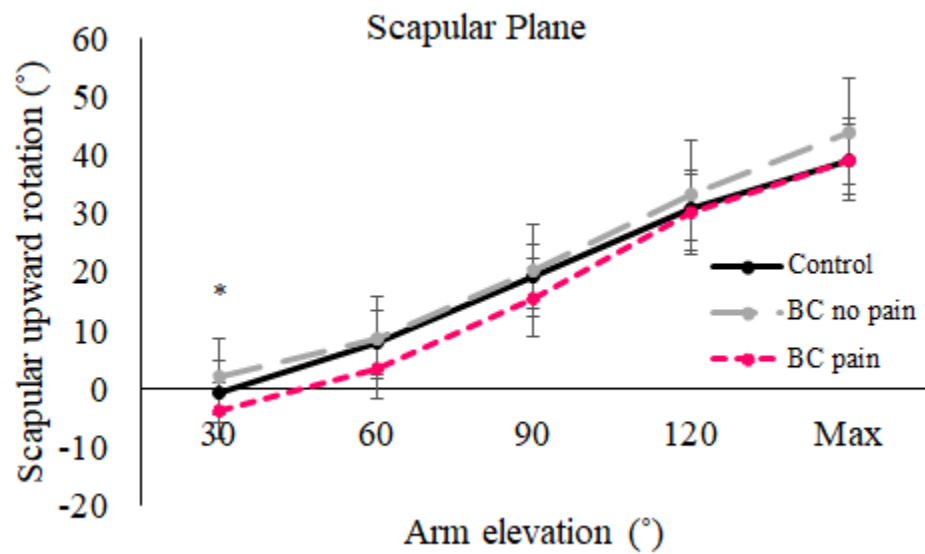
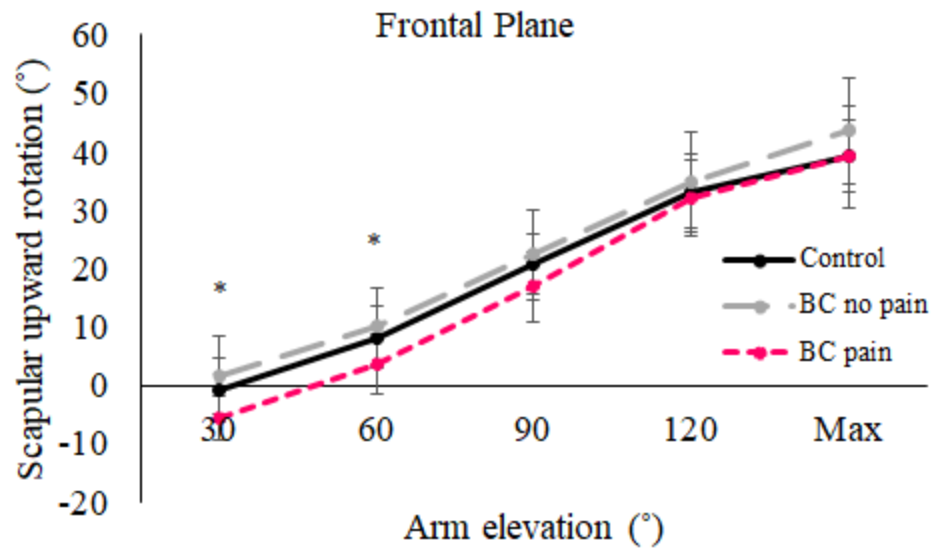
#### **6.3.4 Statistical analysis**

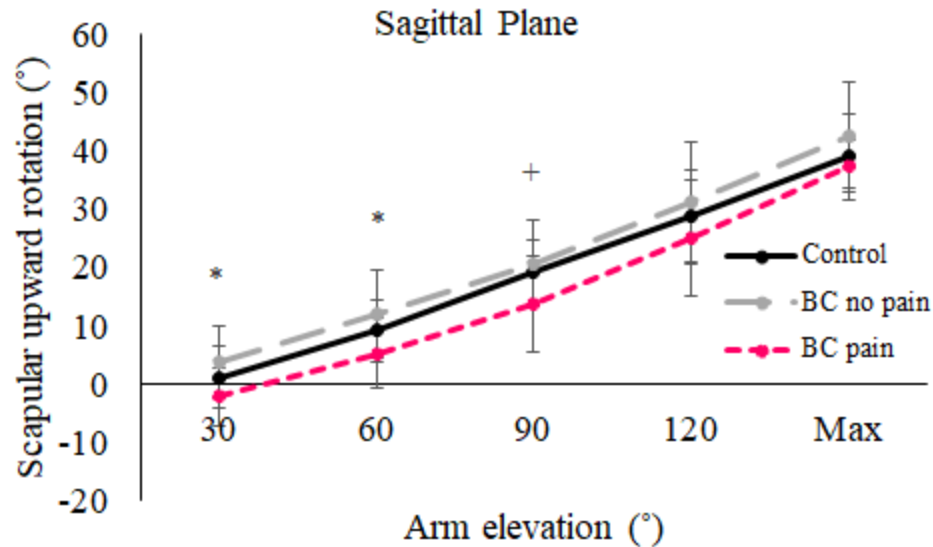
First, scapular upward rotation angle at each humeral elevation angle (30°, 60°, 90°, 120° and maximum) during the arm elevations were compared between the three groups with one-way ANOVAs ( $p < .05$ ) to determine if the differences that were present in the functional tasks also occur during arm elevations. Adjustment of  $p$  values for multiple comparisons was determined to be unnecessary (Armstrong, 2014), because the interpretation of angle differences is already delimited by the accepted error magnitudes of the AMC (3.7° – 10.9°, depending on arm

elevation magnitude). Meaningful differences should be both significant and larger than the reported AMC errors , which helps to eradicate Type 1 error. Second, Pearson correlations were used to determine the relationships between 1) upward rotation angles during elevation and functional tasks and 2) SHR in elevation and in functional tasks. Correlation analyses were stratified by group (control, breast cancer no pain, and breast cancer with pain).

## **6.4 Results**

Scapular upward rotation was significantly lower at lower arm elevations for the breast cancer survivors with pain compared to the breast cancer survivors with no pain (Figure 6.2). While the magnitude of the differences between breast cancer survivors with pain and controls was also substantial (ranging from 3.1° to 5.5°), these comparisons did not reach significance. In the frontal plane, upward rotation at 30° ( $p = .014$ ,  $\eta^2 = .169$ ) and 60° ( $p = .041$ ,  $\eta^2 = .135$ ) were significantly reduced, while in the scapular plane only upward rotation at 30° was lower ( $p = .049$ ,  $\eta^2 = .125$ ). In the sagittal plane, upward rotation angle at 30° ( $p = .045$ ,  $\eta^2 = .126$ ), 60° ( $p = .042$ ,  $\eta^2 = .128$ ), and 90° ( $p = .049$ ,  $\eta^2 = .120$ ) of humeral elevation were different between groups (Figure 6.3), however the difference at 90° of humeral elevation was less than the accepted error for the AMC (6.96° vs 9.0°) (Lang, Kim, et al., 2019), and thus not considered to be meaningful.





**Figure 6.2: Scapular upward rotation throughout arm elevation in the frontal (top), scapular (middle), and sagittal (bottom) planes.**

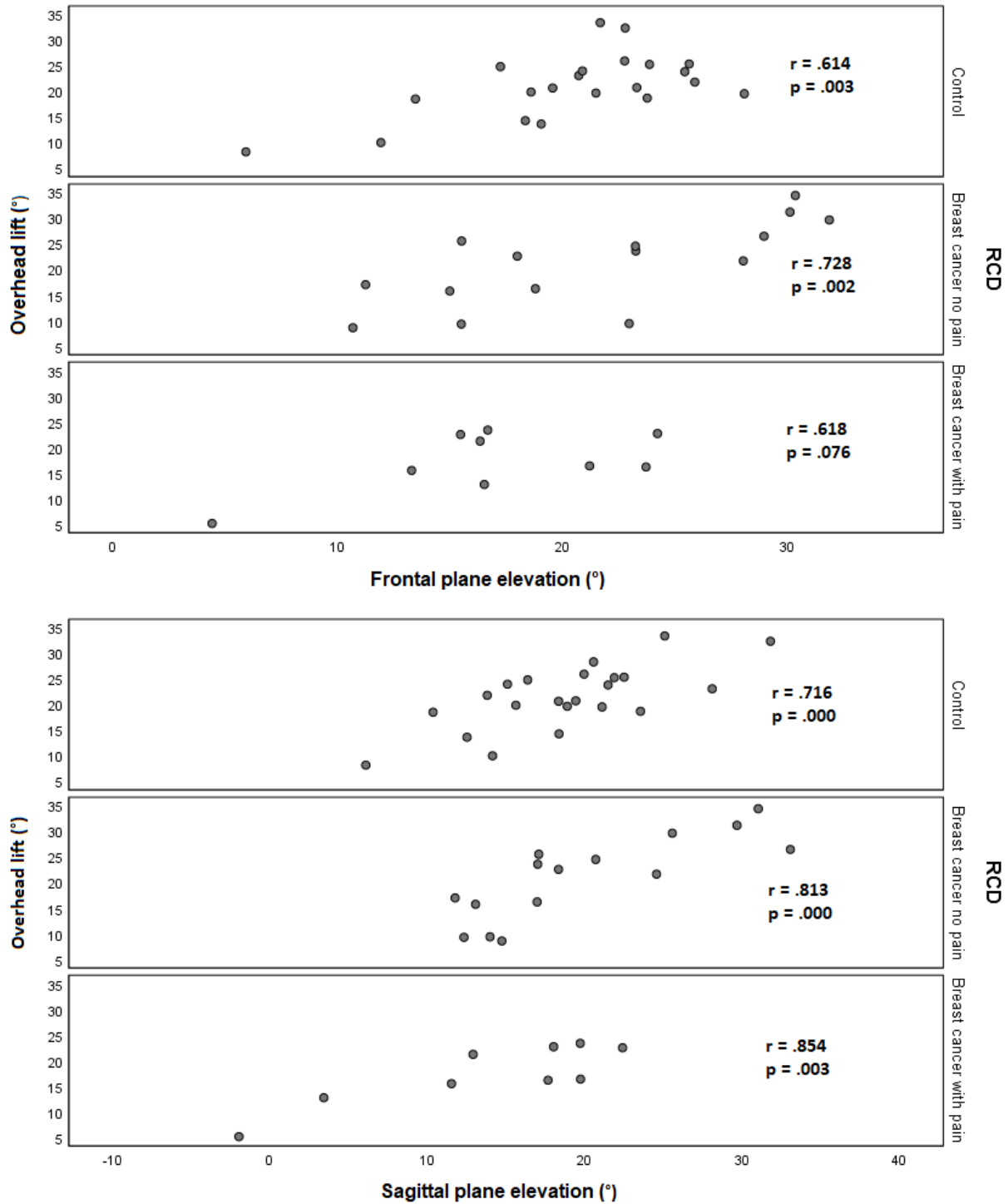
\*denotes significant difference between breast cancer survivors with no pain and breast cancer survivors with pain with a magnitude greater than accepted AMC errors.

+ denotes significant differences between breast cancer survivors with no pain and breast cancer survivors with pain, but magnitude is less than accepted AMC errors.

Scapular upward rotation angle in elevation moderately predicted scapular upward rotation angle during functional tasks. For both the controls and breast cancer with no pain groups, upward rotation angles from three planes were moderately to strongly correlated with upward rotation angle for all functional tasks ( $r = 0.460$  to  $0.958$ ) (Table 6.3). For the breast cancer survivors with pain group, only sagittal plane elevation was consistently moderately to strongly correlated with functional tasks ( $r = 0.691$  to  $0.970$ ) (Figure 6.3).

**Table 6.3: Strength of linear correlation (r) of scapular upward rotation angle during arm elevation in three planes and functional tasks at 60°, 90°, and 120° or maximum humeral elevation. Bolded value signifies significant correlation.**

	Control			Breast cancer no pain			Breast cancer with pain		
	Frontal	Scapular	Sagittal	Frontal	Scapular	Sagittal	Frontal	Scapular	Sagittal
<b>60°</b>									
Overhead Reach Unloaded 60	<b>0.860</b>	<b>0.827</b>	<b>0.747</b>	<b>0.787</b>	<b>0.780</b>	<b>0.898</b>	0.233	0.380	<b>0.754</b>
Overhead Reach Loaded 60	<b>0.901</b>	<b>0.887</b>	<b>0.758</b>	<b>0.824</b>	<b>0.840</b>	<b>0.939</b>	0.031	0.144	0.705
Overhead Lift 60	<b>0.884</b>	<b>0.842</b>	<b>0.881</b>	<b>0.727</b>	<b>0.750</b>	<b>0.834</b>	0.403	0.305	0.691
Fingertip Dexterity Max	<b>0.562</b>	<b>0.459</b>	<b>0.539</b>	<b>0.655</b>	<b>0.633</b>	<b>0.733</b>	0.339	0.368	<b>0.789</b>
Fingertip Dexterity Min	<b>0.573</b>	<b>0.460</b>	<b>0.564</b>	<b>0.646</b>	<b>0.612</b>	<b>0.713</b>	0.292	0.270	<b>0.732</b>
<b>90°</b>									
Overhead Reach Unloaded 90	<b>0.807</b>	<b>0.768</b>	<b>0.619</b>	<b>0.816</b>	<b>0.896</b>	<b>0.944</b>	<b>0.721</b>	<b>0.864</b>	<b>0.970</b>
Overhead Reach Loaded 90	<b>0.892</b>	<b>0.893</b>	<b>0.725</b>	<b>0.860</b>	<b>0.925</b>	<b>0.958</b>	0.636	<b>0.816</b>	<b>0.935</b>
Overhead Lift 90	<b>0.752</b>	<b>0.763</b>	<b>0.716</b>	<b>0.728</b>	<b>0.807</b>	<b>0.813</b>	0.618	<b>0.76</b>	<b>0.854</b>
<b>120°</b>									
Overhead Reach Unloaded at Max	<b>0.540</b>	<b>0.676</b>	<b>0.859</b>	<b>0.737</b>	<b>0.801</b>	<b>0.860</b>	<b>0.754</b>	<b>0.729</b>	<b>0.893</b>
Overhead Reach Loaded at Max	<b>0.594</b>	<b>0.696</b>	<b>0.824</b>	<b>0.766</b>	<b>0.807</b>	<b>0.839</b>	0.571	0.601	<b>0.874</b>
Overhead Lift at Max	<b>0.696</b>	<b>0.689</b>	<b>0.684</b>	<b>0.661</b>	<b>0.756</b>	<b>0.820</b>	0.297	0.381	<b>0.801</b>



**Figure 6.3: Scapular upward rotation angle at 90° during the overhead lift vs elevation in the frontal (top) and sagittal (bottom) planes. Association between the lift and arm elevation is strongest during sagittal elevation.**

SHR during functional tasks was moderately correlated with SHR in elevation from 60° to 90° of humeral elevation. For all three groups, the SHR in the sagittal plane was the most strongly associated for SHR in all functional tasks (Table 6.4). Similar to upward rotation angle, SHR was more strongly correlated for the control and breast cancer with no pain groups.



**Table 6.4: Strength of linear correlation (r) between scapulohumeral rhythm (SHR) during arm elevation in three planes and functional tasks at minimum to 60°, 60° to 90°, and 90° to 120° (arm elevations) or maximum (functional tasks) humeral elevation. Bolded value signifies significant correlation.**

c	Control			Breast cancer no pain			Breast cancer with pain		
	Frontal	Scapular	Sagittal	Frontal	Scapular	Sagittal	Frontal	Scapular	Sagittal
	<b>Min to 60</b>								
<b>Overhead Reach Unloaded min to 60</b>	<b>0.500</b>	0.035	0.413	<b>0.633</b>	<b>0.765</b>	<b>0.729</b>	-0.177	-0.028	0.745
<b>Overhead Reach Loaded min to 60</b>	0.151	0.110	0.277	-0.467	-0.409	-0.157	-0.046	0.306	0.414
<b>Overhead Lift min to 60</b>	-0.171	-0.282	-0.322	0.197	0.280	<b>0.664</b>	-0.400	0.604	0.003
	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>
	<b>60 to 90</b>								
<b>Overhead Reach Unloaded 60 to 90</b>	0.292	<b>0.512</b>	<b>0.627</b>	0.476	0.452	<b>0.691</b>	0.490	0.501	0.333
<b>Overhead Reach Loaded 60 to 90</b>	0.367	<b>0.589</b>	<b>0.657</b>	<b>0.684</b>	<b>0.757</b>	<b>0.959</b>	-0.048	0.410	<b>0.769</b>
<b>Overhead Lift 60 to 90</b>	0.355	<b>0.554</b>	<b>0.457</b>	<b>0.340</b>	<b>0.695</b>	<b>0.946</b>	-0.057	0.662	<b>0.793</b>
<b>Fingertip Dexterity min to max</b>	0.185	<b>0.487</b>	<b>0.533</b>	0.282	0.403	0.144	0.479	0.044	-0.160
	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>	<b>Frontal</b>	<b>Scapular</b>	<b>Sagittal</b>
	<b>90 to 120</b>								
<b>Overhead Reach Unloaded 90 to max</b>	0.205	0.296	<b>0.602</b>	-0.180	0.404	<b>0.738</b>	0.500	0.698	0.082
<b>Overhead Reach Loaded 90 to max</b>	0.329	0.199	0.479	-0.151	<b>0.525</b>	<b>0.914</b>	0.318	<b>0.692</b>	0.214
<b>Overhead Lift 90 to max</b>	0.694	0.294	0.728	-0.020	0.271	0.345	0.220	0.122	-0.172

## 6.5 Discussion

This is one of the first studies to test the relationship of scapular kinematics in arm elevation to scapular kinematics during functional tasks, with the goal of determining the utility of elevation-based clinical evaluation of the scapula. Similar to previously published results of the functional task analysis (Lang, Dickerson, et al., 2019), breast cancer survivors with pain demonstrated reduced upward rotation compared to the other two groups during arm elevation. Upward rotation angles and SHR during elevations demonstrated an overall weak to moderate relationship with the corresponding variables in functional tasks. The control group had a more consistent relationship between the two types of movements, while arm elevation in the sagittal plane in all three groups resulted in scapular kinematics most closely related to those in the functional tasks.

Scapular upward rotation was reduced in breast cancer survivors with pain at lower levels of arm elevation (i.e.  $30^{\circ}$  –  $60^{\circ}$ ) While the reduction in upward rotation was expected, it was expected to occur at the higher levels of arm elevation, such as  $90^{\circ}$ ,  $120^{\circ}$  and maximum, in order to correspond both with the results of functional task performance (Lang, Dickerson, et al., 2019) and a more recent investigation of breast cancer survivor scapula kinematics in scapular elevation (Ribeiro et al., 2019). The results may highlight differing movement strategies during elevation and the loaded, goal-directed functional tasks. Reductions in upward rotation are common in groups with diagnosed rotator cuff disorders or subacromial impingement syndrome (Keshavarz et al., 2017; Ludewig & Reynolds, 2009; Turgut, Duzgun, et al., 2016), and may contribute to development of such disorders. Because the group of breast cancer survivors with pain may not have been clinically diagnosed with shoulder impingement due to positives on only one or two impingement tests (Leong, Ng, Chan, & Fu, 2017; Lukasiewicz et al., 1999), this

alteration is particularly meaningful as it may highlight kinematics that contribute to rotator cuff disorder progression. Previous research reported the opposite results of the current study, finding that breast cancer survivors had substantially higher upward rotation in elevation (Crosbie et al., 2010). However, the populations in that previous work and the current study are distinct: Crosbie et al. (2010) excluded any breast cancer survivors with positives on impingement pain tests or with shoulder pain in the last 6 months. Thus, the opposite patterns of upward rotation may further support the importance of evaluating scapular upward rotation for rotator cuff disorders development in breast cancer survivors. By monitoring upward rotation, this factor could be addressed throughout recovery from breast cancer treatment to mitigate future development of rotator cuff disorders.

Sagittal plane elevation had the strongest relationship to functional task performance, with respect to both scapular upward rotation and SHR. This result supports our hypothesis and is a logical result based on the requirements of the functional tasks. Both the overhead reach and lift involved moving the hand and objects in front of the body, similar to arm elevation in the sagittal plane. However, many scapular kinematic evaluations are performed in the frontal or scapular plane (Huang, Ou, & Lin, 2019; Kijima et al., 2015; Leong et al., 2017; Ribeiro et al., 2019; Robert-Lachaine, Allard, Godbout, Tétreault, & Begon, 2016; Ueda et al., 2019; Walker, Matsuki, Struk, Wright, & Banks, 2015), indicating the discrepancy between clinical evaluation methods and functional task performance. The present findings suggest that scapular kinematics measured during those arm elevations have limited application to common functional task performance.

The lack of strong or significant relationships between SHR in elevation and functional tasks has implications for clinical practice. SHR is an outcome that may be more easily evaluated than

actual scapular angle, and it is also considered an important variable for shoulder function (Bagg & Forrest, 1986; Braman et al., 2009; Fouad Fayad et al., 2008). The limited significant association of SHR in elevations and functional tasks would suggest that the pattern of humeral and scapular movement that occurs during arm elevations may not be the same as while performing functional tasks, suggesting elevation is not an appropriate replacement for functional task analysis. However, our comparison to functional tasks was somewhat limited. Because functional task analysis did not begin with the arm at the side in this particular protocol, the full range of motion could not be compared, which could mean important information was missed. Often the first 30° of an arm elevation, or the “setting phase”, is where reductions in scapular movement affect scapulohumeral rhythm (Braman et al., 2009; Roren et al., 2017).

There are some limitations to this study. Protraction/retraction and anterior/posterior tilt were not tested, as these movements did not emerge as important factors for understanding breast cancer survivor scapular kinematics in previous work. It is possible that these degrees of freedom could be important to assess for breast cancer survivors at different points in recovery (Borstad & Szucs, 2012), or for individuals with other shoulder disorders. Future studies should investigate the relationship of protraction/retraction and posterior/anterior tilt in elevation and relevant functional tasks, for populations in which compensations at those angles are of importance. This study only compared the kinematics of some select work-related functional tasks; thus, it is possible that movements in different planes of humeral motion, such as combing hair or perineal care, would have poorer predictive results from arm elevation. Finally, the sample size, once divided by impingement-pain, resulted in relatively small group (n=9) of breast cancer survivors with pain. Larger numbers would have made for more robust estimates of the relationships in each group.

## **6.6 Conclusion**

There is a weak to moderate relationship between scapular kinematics during arm elevation and functional tasks, but there is not enough evidence to confirm that evaluation of arm elevation would provide sufficient information to infer kinematics for functional task performance. Future work should further explore the utility of these functional tasks for scapular motion evaluation in order to make strong recommendations for changes to clinical practice guidelines.

## CHAPTER 7: CONCLUSIONS

The goal of this dissertation was to analyze shoulder biomechanics for breast cancer survivors during arm-centric tasks. These data can be used as an initial basis for targeted rehabilitation information for both clinicians and survivors regarding possible limitations and treatment recommendations. The following research questions were addressed:

1. Can the scapulae of breast cancer survivors and age-group-matched controls be tracked with sufficient accuracy with the acromial marker cluster (AMC)?
2. Are torso and shoulder kinematics during arm-centric functional task performance different for breast cancer survivors than non-cancer controls?
3. Are muscle force strategies during functional tasks different for breast cancer survivors than age-group-matched controls?
4. Is scapular motion during arm elevation associated with scapular motion in functional tasks for breast cancer survivors and non-cancer controls?

The primary outcome of the first manuscript established the utility of the AMC in this non-normative sample. The AMC has been used to track the scapula in previous research, but all investigations into the accuracy of this method have been performed on young, lean, impairment-free individuals (Karduna et al., 2001; Maclean et al., 2014; Meskers et al., 2007; van Andel et al., 2009; Warner et al., 2012). When using the double calibration method (Brochard et al., 2011), the AMC was able to track dynamic motion of breast cancer survivors and age-group-matched controls with errors in ranges previously reported as acceptable (Karduna et al., 2001; Maclean et al., 2014; Meskers et al., 2007; van Andel et al., 2009; Warner et al., 2012).

Quantifying these errors not only enhances confidence when using the AMC for scapular motion tracking, but also when identifying differences between groups; significant between-group

differences larger than the defined error magnitudes can be considered meaningful with confidence.

The primary outcome of the second manuscript was the identification of scapular compensations in breast cancer survivors. When breast cancer survivors were divided based on the presence of pain in impingement provocation tests, the group with pain demonstrated reduced scapular upward rotation during the overhead reach and overhead lift, with trends toward decreased humeral abduction and internal rotation in extreme positions of the repetitive reach and overhead lift tasks as well. These compensations are associated with rotator cuff injury diagnosis (Keshavarz et al., 2017; Ludewig & Cook, 2000; Turgut, Pedersen, Duzgun, & Baltaci, 2016); decreased upward rotation of the scapula, in particular, may cause mechanical impingement of the supraspinatus (Brossmann et al., 1996) or overload of the supraspinatus tendon, which could be responsible for the pain in the provocation tests. Supraspinatus tendon damage is often considered the first step towards more severe shoulder injuries, as it can lead to rotator cuff tears and biceps tendon rupture if left untreated. This is the first study to directly connect post-surgery status to kinematic compensations and provide evidence for the proposed relationship between breast cancer treatment and rotator cuff disorders.

This second study also defined the kinematics of the full upper limb during a return-to-work protocol. While the differences between groups were limited to those discussed above, the lack of torso and humeral kinematic changes by breast cancer survivors is, in itself, notable. Still, breast cancer survivors, both with and without impingement-related pain, performed the tasks at a lower capacity than controls, meaning they moved slower, less precisely, and could lift and hold less weight. They also reported, on average, higher perceived disability than controls. While these limitations did not result in any torso-humeral compensations, some other strategy

compensations were noted, anecdotally. Combined with decreased capacity, these results have implications for return-to-work for breast cancer survivors. Both workstation set up and physical demands should be considered when determining return-to-work ability.

There are two main contributions of the third manuscript of this dissertation. First, SLAM can be successfully modified to model breast cancer survivors and age-group-matched controls.

Typically the model uses a scapulohumeral rhythm regression equation to calculate scapular positioning, but here measured orientations were input with reasonable success, allowing the previously identified compensations to be captured. To this author's knowledge, no other models have attempted to predict muscle forces for breast cancer survivors or individuals with rotator cuff disorders during functional tasks with these diverse demands. While there are acknowledged limitations of this model, notably the lack of antagonistic co-contraction typical of efficiency-based optimization formulations (Dickerson et al., 2007), its utility for comparing these groups is positive. The second contribution from this study was the comparison of predicted muscle forces between breast cancer survivors, with and without pain, and controls. The model predicted muscle force patterns consistent with kinematic alterations. The upper trapezius was more active in the breast cancer survivors with pain, similar to other investigations of both breast cancer survivors and individuals with rotator cuff disorders (Brookham et al., 2018b; Galiano-Castillo et al., 2011). Other muscles also demonstrated higher activity, including the supraspinatus and pectoralis major muscles. While it was hypothesized based on the kinematics from the second study that the pain was related to impingement of the supraspinatus tendon, these results support another possibility; the pain and disability could be related to overload of the tendon, after a period of under loading during recovery from surgery. The unprecedented direct connection to



potentially harmful kinematics makes these results uniquely able to generate a basis for rehabilitation recommendations, as outlined later in this chapter.

Finally, the fourth manuscript's primary contribution is the quantification of the relationship between arm elevation and functional task performance with regards to scapular motion.

Scapular upward rotation was most closely related during sagittal plane elevation and overhead reaching and lifting. However, the magnitude and timing of differences present in breast cancer survivors with pain during functional task performance were not present to the same level during arm elevation in any plane. This result suggests that assessment during arm elevation may not provide enough information to determine the implications for daily life, even though this is the common practice in both clinical practice (Uhl et al., 2009) and laboratory investigations (Keshavarz et al., 2017).

## **7.1 Limitations**

There are some limitations that affect the overall conclusions and implications of these results.

First, the lack of longitudinal analysis of kinematics and information about pre-treatment impingement status delimits any commentary on the cause versus association relationship of pain and kinematics. Second, the differences between groups were present on the right, and dominant, side of the participants. A larger sample size, with more deliberate inclusion of left-hand dominant breast cancer survivors would help to parse out the effects of handedness on kinematic compensations after breast cancer treatment. Finally, glenohumeral joint translation was not measured in this study. While this is difficult to measure, it is accepted in the clinical community as an important aspect of motion (Dal Maso et al., 2015); reduced mobility within the glenohumeral joint can cause subsequent capsular tightness that may contribute to overall shoulder biomechanical compensations.

## **7.2 Future Research Recommendations**

This combination of studies has identified several gaps that could benefit from future research. Functional task performance and scapular motion should be more robustly defined with breast cancer survivors after a variety of treatments, and particularly breast reconstruction and radiation (Bentzen et al., 1989). Additionally, tracking scapular motion of breast cancer survivors over time will enable more precise identification of a cause/effect relationship of pain, disability, and kinematic compensations. To further these recommendations, interventions to both treat and prevent harmful kinematic alterations should be performed. Results support early intervention for injury prevention in breast cancer survivors. Scapular positioning training involving stretching and strengthening agonist and antagonist muscles, as well as neuromuscular cues and exercises, could help decrease the activity in these muscles to prevent insufficient upward rotation and overuse/injury of the supraspinatus. Future work should test these prophylactic recommendations for their influence on scapular kinematics and muscle force strategies. Finally, careful validation of clinical methods for measuring scapular upward rotation is needed to translate these high-resolution biomechanical outcomes to clinical application. The current results support the use of a functional task instead of single-plane arm elevation for scapular motion assessment of breast cancer survivors. Due to the relative ease of set up and execution, and the demonstrated kinematic differences during performance, the overhead reach should be further explored to add to both scientific and clinical practice guidelines. Future research should work towards a more robust definition of normative and pathological kinematics during this task.

### **7.3 Implications**

The kinematic, kinetic, and clinical data presented here combine to create recommendations that can be useful to clinicians, scientists, and breast cancer survivors. Based on these results, a prospective treatment model, a method that has previously been suggested for other upper limb limitations (McNeely et al., 2010; Stout et al., 2016), for breast cancer survivors focused on rotator cuff injury prevention strategies should be tested. It is recommended that scapular upward rotation be monitored from pre-treatment to several months and years post-treatment to identify any pre-dispositions or post-treatment alterations that may occur and lead to pain and subacromial impingement or supraspinatus tendon overload. Muscle force prediction differences suggest that rehabilitation efforts should focus on inhibiting the upper trapezius muscle through strategic strengthening, stretching, and neuromuscular training of the muscles surrounding the shoulder, but the specific intervention needs further investigation to refine. Finally, if arm elevation is chosen for the evaluation protocol, motion during the sagittal plane should be the movement used for analysis; however, it is recommended that a simple loaded reach be used for assessment of scapular kinematics in breast cancer survivors, and possibly for other individuals with shoulder pathologies. The strategy is certainly feasible for fundamental scientific evaluation, but can also be useful and practical in clinical practice. Overall, the novel research questions and innovative methods of this thesis supply important information for post-breast cancer shoulder dysfunction and will be used to disseminate rehabilitation recommendations and direct future research.

## REFERENCES

- Aerts, P. D. M., De Vries, J., Van Der Steeg, A. F. W., & Roukema, J. A. (2011). The relationship between morbidity after axillary surgery and long-term quality of life in breast cancer patients: The role of anxiety. *European Journal of Surgical Oncology*, 37(4), 344–349. <https://doi.org/10.1016/j.ejso.2011.01.016>
- Ahn, E., Cho, J., Shin, D. W., Park, B. W., Ahn, S. H., Noh, D. Y., ... Yun, Y. H. (2009). Impact of breast cancer diagnosis and treatment on work-related life and factors affecting them. *Breast Cancer Research and Treatment*, 116(3), 609–616. <https://doi.org/10.1007/s10549-008-0209-9>
- AJCC. (2009). Breast Cancer Staging. Retrieved December 14, 2016, from <https://cancerstaging.org/references-tools/quickreferences/Pages/default.aspx>
- An, K. N., Kwak, B. M., Chao, E. Y., & Morrey, B. F. (1984). Determination of Muscle and Joint Forces: A New Technique to Solve the Indeterminate Problem. *Journal of Biomechanical Engineering*, 106(4), 364–367. Retrieved from <http://dx.doi.org/10.1115/1.3138507>
- Anderson, N. B., & Armstead, C. A. (1995). Toward Understanding the Association of Socioeconomic-Status and Health - A New Challenge for Biopsychosocial Approach. *Psychosomatic Medicine*, 57(3), 213–225.
- Arjmand, N., & Shirazi-Adl, A. (2005). Biomechanics of changes in lumbar posture in static lifting. *Spine*, 30(23), 2637–2648. <https://doi.org/10.1097/01.brs.0000187907.02910.4f>
- Armstrong, R. A. (2014). When to use the Bonferroni correction. *Ophthalmic & Physiological Optics*, 34, 502–508. <https://doi.org/10.1111/opo.12131>
- Assis, M. R., Marx, A. G., Magna, L. A., & Ferrigno, I. S. V. (2013). Late morbidity in upper limb function and quality of life in women after breast cancer surgery. *Brazilian Journal of Physical Therapy*, 17(3), 236–243. <https://doi.org/10.1590/S1413-35552012005000088>
- Bagg, S. D., & Forrest, W. J. (1986). Electromyographic study of the scapular rotators during arm abduction in the scapular plane. *American Journal of Physical Medicine*, 65(3), 111–124.
- Bagg, S. D., & Forrest, W. J. (1988). A biomechanical analysis of scapular rotation during arm abduction in the scapular plane. *American Journal of Physical Medicine & Rehabilitation / Association of Academic Physiatrists*. <https://doi.org/10.1097/JSM.0b013e31822179e8>
- Balzarini, A., Lualdi, P., Lucarini, C., Ferla, S., Galli, M., Crivellini, M., & DeConno, F. (2006). Biomechanical evaluation of scapular girdle in patients with chronic arm lymphedema. *Lymphology*, 39(3), 132–140. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/?term=BALZARINI+%2C+LUALDI>
- Barnett, N. D., Duncan, R. D. D., & Johnson, G. R. (1999). The measurement of three dimensional scapulohumeral kinematics - a study of reliability. *Clinical Biomechanics*, 14, 287–290.

- Bentzen, S. M., Overgaard, M., & Thames, H. D. (1989). Fractionation sensitivity of a functional endpoint: impaired shoulder movement after post-mastectomy radiotherapy. *International Journal of Radiation Oncology, Biology, Physics*, 17(3), 531–537. [https://doi.org/10.1016/0360-3016\(89\)90103-X](https://doi.org/10.1016/0360-3016(89)90103-X)
- Beurskens, C. H. G., van Uden, C. J. T., Strobbe, L. J. a, Oostendorp, R. a B., & Wobbes, T. (2007). The efficacy of physiotherapy upon shoulder function following axillary dissection in breast cancer, a randomized controlled study. *BMC Cancer*, 7, 166. <https://doi.org/10.1186/1471-2407-7-166>
- Blache, Y., Maso, F. D., Desmoulins, L., Plamondon, A., & Begon, M. (2015). Superficial shoulder muscle co-activations during lifting tasks: Influence of lifting height , weight and phase. *Journal of Electromyography and Kinesiology*, 25, 355–362. <https://doi.org/10.1016/j.jelekin.2014.11.004>
- Bolsterlee, B., Veeger, D. H. E. J. E. J., & Chadwick, E. K. (2013). Clinical applications of musculoskeletal modelling for the shoulder and upper limb. *Medical and Biological Engineering and Computing*, 51(9), 953–963. <https://doi.org/10.1007/s11517-013-1099-5>
- Borstad, J. D., & Ludewig, P. M. (2002). Comparison of scapular kinematics between elevation and lowering of the arm in the scapular plane. *Clinical Biomechanics*, 17, 650–659. [https://doi.org/10.1016/S0268-0033\(02\)00136-5](https://doi.org/10.1016/S0268-0033(02)00136-5)
- Borstad, J. D., & Szucs, K. A. (2012). Three-dimensional scapula kinematics and shoulder function examined before and after surgical treatment for breast cancer. *Human Movement Science*, 31(2), 408–418. <https://doi.org/10.1016/j.humov.2011.04.002>
- Bosompra, K., Ashikaga, T., Brien, P. J. O., Nelson, L., & Skelly, J. (2002). Swelling, Numbness, Pain, and Their Relationship to Arm Function Among Breast Cancer Survivors : A Disablement Process Model Perspective. *The Breast Journal*, 8(6), 338–348.
- Box, R. C., Reul-Hirche, H. M., Bullock-Saxton, J. E., & Furnival, C. M. (2002). Shoulder movement after breast cancer surgery: results of a randomised controlled study of postoperative physiotherapy. *Breast Cancer Res Treat*, 75(1), 35–50.
- Braman, J. P., Engel, S. C., LaPrade, R. F., & Ludewig, P. M. (2009). In vivo assessment of scapulohumeral rhythm during unconstrained overhead reaching in asymptomatic subjects. *Journal of Shoulder and Elbow Surgery*, 18, 960–967. <https://doi.org/10.1016/j.jse.2009.02.001>
- Brennan, M. J. (1992). Lymphedema following the surgical treatment of breast cancer: A review of pathophysiology and treatment. *Journal of Pain and Symptom Management*. [https://doi.org/10.1016/0885-3924\(92\)90122-X](https://doi.org/10.1016/0885-3924(92)90122-X)
- Brochard, S., Lempereur, M., & Rémy-Néris, O. (2011). Double calibration: An accurate, reliable and easy-to-use method for 3D scapular motion analysis. *Journal of Biomechanics*, 44(4), 751–754. <https://doi.org/10.1016/j.jbiomech.2010.11.017>
- Brookham, R. L. (2014). *Quantifying and predicting upper limb capability and dysfunction of breast cancer survivors*. University of Waterloo.
- Brookham, R. L., Cudlip, A. C., & Dickerson, C. R. (2018a). Examining upper limb kinematics

- and dysfunction of breast cancer survivors in functional dynamic tasks. *Clinical Biomechanics*, 55, 86–93. <https://doi.org/10.1016/j.clinbiomech.2018.04.010>
- Brookham, R. L., Cudlip, A. C., & Dickerson, C. R. (2018b). Quantification of upper limb electromyographic measures and dysfunction of breast cancer survivors during performance of functional dynamic tasks. *Clinical Biomechanics*, 52(December 2017), 7–13. <https://doi.org/10.1016/j.clinbiomech.2017.12.011>
- Brossmann, J., Preidler, K. W., Pedowitz, R. A., White, L. M., Trudell, D., & Resnick, D. (1996). Shoulder impingement syndrome: influence of shoulder position on rotator cuff impingement - an anatomic study. *American Journal of Roentgenology*, 167, 1511–1515.
- Caban, M. E., Freeman, J. L., Zhang, D. D., Jansen, C., Ostir, G., Hatch, S. S., & Goodwin, J. S. (2006). The relationship between depressive symptoms and shoulder mobility among older women: assessment at one year after breast cancer diagnosis. *Clinical Rehabilitation*, 20(6), 513–522. <https://doi.org/10.1191/0269215506cr966oa>
- Calis, M. (2000). Diagnostic values of clinical diagnostic tests in subacromial impingement syndrome. *Annals of the Rheumatic Diseases*, 59(1), 44–47. <https://doi.org/10.1136/ard.59.1.44>
- Callaghan, J. P., Gunning, J. L., & McGill, S. M. (1998). The relationship between lumbar spine load and muscle activity during extensor exercises. *Physical Therapy*, 78(1), 8–18. Retrieved from <http://ptjournal.apta.org/content/78/1/8.short>
- Campbell, S. T., Ecklund, K. J., Chu, E. H., McGarry, M. H., Gupta, R., & Lee, T. Q. (2014). The role of pectoralis major and latissimus dorsi muscles in a biomechanical model of massive rotator cuff tear. *Journal of Shoulder and Elbow Surgery*, 23(8), 1136–1142. <https://doi.org/10.1016/j.jse.2013.11.030>
- Canadian Breast Cancer Network. (2010). Breast Cancer: Economic Impact and Labour Force Re-Entry. *International Immunology*, 24(4), 44. <https://doi.org/10.1093/intimm/dxs023>
- Canadian Cancer Society. (2015). *Canadian Cancer Statistics 2015*. Toronto, ON. Retrieved from [http://www.cancer.ca/~media/cancer.ca/CW/cancer information/cancer 101/Canadian cancer statistics/Canadian-Cancer-Statistics-2015-EN.pdf?la=en](http://www.cancer.ca/~media/cancer.ca/CW/cancer%20information/cancer%20101/Canadian%20cancer%20statistics/Canadian-Cancer-Statistics-2015-EN.pdf?la=en)
- Canadian Cancer Society. (2016). What is breast cancer? Retrieved November 22, 2016, from <http://www.cancer.ca/en/cancer-information/cancer-type/breast/breast-cancer/?region=on>
- Cantarero-Villanueva, I., Fernández-Lao, C., Díaz-Rodríguez, L., Fernández-de-las-Peñas, C., Ruiz, J. R., & Arroyo-Morales, M. (2012). The Handgrip Strength Test as a Measure of Function in Breast Cancer Survivors. *American Journal of Physical Medicine & Rehabilitation*, 91(9), 774–782. <https://doi.org/10.1097/PHM.0b013e31825f1538>
- Carter, C. L., Allen, C., & Henson, D. E. (1989). Relation of tumor size, lymph node status, and survival in 24,740 breast cancer cases. *Cancer*, 63(1), 181–187. <https://doi.org/10.1097/00006534-198911000-00055>
- Challis, J. H. (1997). Producing physiologically realistic individual muscle force estimations by imposing constraints when using optimization techniques. *Medical Engineering and Physics*, 19(3), 253–261. [https://doi.org/10.1016/S1350-4533\(96\)00062-8](https://doi.org/10.1016/S1350-4533(96)00062-8)

- Chan, D. N. S., Lui, L. Y., & So, W. K. W. (2010). Effectiveness of exercise programmes on shoulder mobility and lymphoedema after axillary lymph node dissection for breast cancer: systematic review. *Journal of Advanced Nursing*, 66(9), 1902–1914. <https://doi.org/10.1111/j.1365-2648.2010.05374.x>
- Chen, D., Lai, L., Duan, C., Yan, M., Xing, M., Chen, J., & Zhang, F. (2014). Conservative surgery plus axillary radiotherapy vs. modified radical mastectomy in patients with stage i breast cancer. *Clinical Breast Cancer*, 14(1), e10-3. <https://doi.org/10.1016/j.clbc.2013.09.007>
- Chetty, U., Jack, W., Prescott, R. J., Tyler, C., & Rodger, a. (2000). Management of the axilla in operable breast cancer treated by breast conservation: a randomized clinical trial. Edinburgh Breast Unit. *The British Journal of Surgery*, 87(2), 163–169. <https://doi.org/10.1046/j.1365-2168.2000.01345.x>
- Chopp-Hurley, J. N., Brookham, R. L., & Dickerson, C. R. (2016). Identification of potential compensatory muscle strategies in a breast cancer survivor population: A combined computational and experimental approach. *Clinical Biomechanics*, 40, 63–67. <https://doi.org/10.1016/j.clinbiomech.2016.10.015>
- Cohen, R. B., & Williams, G. R. (1998). Impingement syndrome and rotator cuff disease as repetitive motion disorders. *Clinical Orthopaedics and Related Research*, 351, 95–101.
- Côté, J. N., Raymond, D., Mathieu, P. A., Feldman, A. G., & Levin, M. F. (2005). Differences in multi-joint kinematic patterns of repetitive hammering in healthy, fatigued and shoulder-injured individuals. *Clinical Biomechanics*, 20(6), 581–590. <https://doi.org/10.1016/j.clinbiomech.2005.02.012>
- Cram, J. R., & Kasman, G. S. (1998). *Cram's Introduction to Surface Electromyography* (2nd Editio). Mississauga, ON: Jones and Bartlett Publishers.
- Crane-Okada, R., Wascher, R. a, Elashoff, D., & Giuliano, A. E. (2008). Long-term morbidity of sentinel node biopsy versus complete axillary dissection for unilateral breast cancer. *Annals of Surgical Oncology*, 15(7), 1996–2005. <https://doi.org/10.1245/s10434-008-9909-y>
- Crosbie, J., Kilbreath, S. L., Dylke, E., Refshauge, K. M., Nicholson, L. L., Beith, J. M., ... White, K. (2010). Effects of mastectomy on shoulder and spinal kinematics during bilateral upper-limb movement. *Physical Therapy*, 90(5), 679–692.
- Crowninshield, R. D., & Brand, R. A. (1981). A physiologically based criterion of muscle force prediction in locomotion. *Journal of Biomechanics*, 14(11), 793–801. [https://doi.org/http://dx.doi.org/10.1016/0021-9290\(81\)90035-X](https://doi.org/http://dx.doi.org/10.1016/0021-9290(81)90035-X)
- Cutti, A. G., & Veeger, H. E. J. (2009). Shoulder biomechanics: Today's consensus and tomorrow's perspectives. *Medical and Biological Engineering and Computing*, 47(5 SPEC. ISS.), 463–466. <https://doi.org/10.1007/s11517-009-0487-3>
- da Costa, B. R., Armijo-Olivo, S., Gadotti, I., Warren, S., Reid, D. C., & Magee, D. J. (2010). Reliability of scapular positioning measurement procedure using the Palpation Meter (PALM). *Physiotherapy*, 96(1), 59–67. <https://doi.org/10.1016/j.physio.2009.06.007>
- Dal Maso, F., Raison, M., Lundberg, A., Arndt, A., Allard, P., & Begon, M. (2015).

- Glenohumeral translations during range-of-motion movements, activities of daily living, and sports activities in healthy participants. *Clinical Biomechanics*, 30(9), 1002–1007.
- Dalberg, K., Krawiec, K., & Sandelin, K. (2010). Eleven-year follow-up of a randomized study of pectoral fascia preservation after mastectomy for early breast cancer. *World Journal of Surgery*, 34(11), 2539–2544. <https://doi.org/10.1007/s00268-010-0737-4>
- Dark, A., Ginn, K. A., & Halaki, M. (2007). Shoulder muscle recruitment patterns during commonly used rotator cuff exercises: an electromyographic study. *Physical Therapy*, 87(8), 1039–1046.
- Dawes, D. J., Meterissian, S., Goldberg, M., & Mayo, N. E. (2008). Impact of lymphoedema on arm function and health-related quality of life in women following breast cancer surgery. *Journal of Rehabilitation Medicine*, 40(8), 651–658. <https://doi.org/10.2340/16501977-0232>
- de Boer, A. G. E. M., Taskila, T., Ojajarvi, A., van Dijk, F. J. H., & Verbeek, J. H. A. . (2009). Cancer survivors and unemployment. *Journal of American Medical Association*, 301(7), 753–762. <https://doi.org/10.1001/jama.293.3.349>
- De Groef, A., Van Kampen, M., Tieto, E., Schwonweger, P., Christiaens, M., Neven, P., ... Devoogdt, N. (2016). Arm lymphoedema and upper limb impairments in sentinel node-negative breast cancer patients : A one year follow-up study Arm lymphoedema and upper limb impairments in sentinel node-negative breast cancer patients : A one year follow-up study. *The Breast*, 29, 102–108. <https://doi.org/10.1016/j.breast.2016.07.021>
- de Groot, J. H., & Brand, R. (2001). A three-dimensional regression model of the shoulder rhythm. *Clinical Biomechanics*, 16, 735–743. [https://doi.org/10.1016/S0268-0033\(01\)00065-1](https://doi.org/10.1016/S0268-0033(01)00065-1)
- de Haan, A., Toor, A., Hage, J. J., Veeger, H. E. J., & Woerdeman, L. a E. (2007). Function of the pectoralis major muscle after combined skin-sparing mastectomy and immediate reconstruction by subpectoral implantation of a prosthesis. *Annals of Plastic Surgery*, 59(6), 605–610. <https://doi.org/10.1097/SAP.0b013e31803429dd>
- Devoogdt, N., Van Kampen, M., Christiaens, M. R., Troosters, T., Piot, W., Beets, N., ... Gosselink, R. (2011). Short- and long-term recovery of upper limb function after axillary lymph node dissection. *European Journal of Cancer Care*, 20(1), 77–86. <https://doi.org/10.1111/j.1365-2354.2009.01141.x>
- Dickerson, C. R., Chaffin, D. B., & Hughes, R. E. (2007). A mathematical musculoskeletal shoulder model for proactive ergonomic analysis. *Computer Methods in Biomechanics and Biomedical Engineering*, 10(6), 389–400. <https://doi.org/10.1080/10255840701592727>
- Dickerson, C. R., Hughes, R. E., & Chaffin, D. B. (2008). Experimental evaluation of a computational shoulder musculoskeletal model. *Clinical Biomechanics*, 23(7), 886–894. <https://doi.org/10.1016/j.clinbiomech.2008.04.004>
- Disselhorst-klug, C., Schmitz-rode, T., & Rau, G. (2009). Surface electromyography and muscle force : Limits in sEMG – force relationship and new approaches for applications. *Clinical Biomechanics*, 24, 225–235. <https://doi.org/10.1016/j.clinbiomech.2008.08.003>



- Doiron, Y., Delacroix, S., Denninger, M., & Simoneau, M. (2010). Kinetic strategies of patients with shoulder impingement syndrome. *Journal of Orthopaedic Research*, 28(1), 6–11. <https://doi.org/10.1002/jor.20940>
- Drake, J. D. M., & Callaghan, J. P. (2006). Elimination of electrocardiogram contamination from electromyogram signals: An evaluation of currently used removal techniques. *Journal of Electromyography and Kinesiology*, 16(2), 175–187. <https://doi.org/10.1016/j.jelekin.2005.07.003>
- Drolet, M., Maunsell, E., Brisson, J., Brisson, C., Mâsse, B., & Deschênes, L. (2005). Not working 3 years after breast cancer: Predictors in a population-based study. *Journal of Clinical Oncology*, 23(33), 8305–8312. <https://doi.org/10.1200/JCO.2005.09.500>
- Drolet, M., Maunsell, E., Mondor, M., Brisson, C., Brisson, J., Mâsse, B., & Deschênes, L. (2005). Work absence after breast cancer diagnosis: A population-based study. *Cmaj*, 173(7), 765–769. <https://doi.org/10.1503/cmaj.050178>
- Dul, J., Johnson, G. E., Shiavi, R., & Townsend, M. A. (1984). Muscular synergism-II. A minimum-fatigue criterion for load sharing between synergistic muscles. *Journal of Biomechanics*, 17(9), 675–684. [https://doi.org/10.1016/0021-9290\(84\)90121-0](https://doi.org/10.1016/0021-9290(84)90121-0)
- Ebaugh, D., Spinelli, B., & Schmitz, K. H. (2011). Shoulder impairments and their association with symptomatic rotator cuff disease in breast cancer survivors. *Medical Hypotheses*, 77(4), 481–487. <https://doi.org/10.1016/j.mehy.2011.06.015>
- Elliott, D., Roy, E. a., Goodman, D., Carson, R. G., Chua, R., & Maraj, B. K. V. (1993). Asymmetries in the preparation and control of manual aiming movements. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, 47(3), 570–589. <https://doi.org/10.1037/h0078856>
- Fayad, F., Hoffmann, G., Hanneton, S., Yazbeck, C., Lefevre-colau, M. M., Poiraudau, S., ... Roby-Brami, A. (2006). 3-D scapular kinematics during arm elevation: Effect of motion velocity. *Clinical Biomechanics*. <https://doi.org/10.1016/j.clinbiomech.2006.04.015>
- Fayad, Fouad, Roby-Brami, A., Yazbeck, C., Hanneton, S., Lefevre-Colau, M. M., Gautheron, V., ... Revel, M. (2008). Three-dimensional scapular kinematics and scapulohumeral rhythm in patients with glenohumeral osteoarthritis or frozen shoulder. *Journal of Biomechanics*, 41(2), 326–332. <https://doi.org/10.1016/j.jbiomech.2007.09.004>
- Galiano-Castillo, N., Fernandez-Lao, C., Cantarero-Villanueva, I., Fernandez-de-Las-Penas, C., Menjon-Beltran, S., & Arroyo-Morales, M. (2011). Altered pattern of cervical muscle activation during performance of a functional upper limb task in breast cancer survivors. *American Journal of Physical Medicine & Rehabilitation / Association of Academic Physiatrists*, 90(5), 349–355. <https://doi.org/10.1097/PHM.0b013e318214e406>
- Gosselink, R., Rouffaer, L., Vanhelden, P., Piot, W., Troosters, T., & Christiaens, M.-R. R. (2003). Recovery of upper limb function after axillary dissection. *Journal of Surgical Oncology*, 83(4), 204–211. <https://doi.org/10.1002/jso.10271>
- Grewal, T. J., & Dickerson, C. R. (2013). A novel three-dimensional shoulder rhythm definition that includes overhead and axially rotated humeral postures. *Journal of Biomechanics*,

46(3), 608–611. <https://doi.org/10.1016/j.jbiomech.2012.09.028>

- Hack, T. F., Cohen, L., Katz, J., Robson, L. S., & Goss, P. (1999). Physical and psychological morbidity after axillary lymph node dissection for breast cancer. *Journal of Clinical Oncology*, 17(1), 143–149.
- Haffty, B. G., Goldberg, N. B., Fischer, D., McKhann, C., Beinfield, M., Weissberg, J. B., ... Gerald, W. (1989). Conservative surgery and radiation therapy in breast carcinoma: local recurrence and prognostic implications. *International Journal of Radiation Oncology*, 17, 727–732.
- Halsted, W. S. (1894). The results of operations for the cure of cancer of the breast performed at the Johns Hopkins Hospital from June, 1889, to January, 1894. *Annals of Surgery*, 20(5), 497. <https://doi.org/10.1097/00000658-189407000-00075>
- Hamill, J., Van Emmerik, R. E. A., Heiderscheit, B. C., & Li, L. (2009). A dynamical systems approach to lower extremity running injuries. *Clinical Biomechanics*, 14, 297–308.
- Hayes, S., Battistutta, D., & Newman, B. (2005). Objective and subjective upper body function six months following diagnosis of breast cancer. *Breast Cancer Research and Treatment*, 94(1), 1–10. <https://doi.org/10.1007/s10549-005-5991-z>
- Hayes, S., Rye, S., Battistutta, D., DiSipio, T., & Newman, B. (2010). Upper-body morbidity following breast cancer treatment is common, may persist longer-term and adversely influences quality of life. *Health and Quality of Life Outcomes*, 8(92), 3–9. Retrieved from <http://cyber.usask.ca/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=rzh&AN=104349314&site=ehost-live>
- Hickey, B. W., Milosavljevic, S., Bell, M. L., & Milburn, P. D. (2007). Accuracy and reliability of observational motion analysis in identifying shoulder symptoms. *Manual Therapy*, 12(3), 263–270. <https://doi.org/10.1016/j.math.2006.05.005>
- Hogfors, C., Sigholm, G., & Herberts, P. (1987). Biomechanical model of the human shoulder - I. Elements. *Journal of Biomechanics*, 20(2), 157–166. [https://doi.org/10.1016/0021-9290\(87\)90307-1](https://doi.org/10.1016/0021-9290(87)90307-1)
- Hojris, I., Andersen, J., Overgaard, M., & Overgaard, J. (2000). Late treatment-related morbidity in breast cancer patients randomized to postmastectomy radiotherapy and systemic treatment versus systemic treatment alone. *Acta Oncol*, 39(3), 355–372. <https://doi.org/10.1080/028418600750013131>
- Holm, I., Bolstad, B., Lütken, T., Ervik, A., Røkkum, M., & Steen, H. (2000). Reliability of goniometric measurements and visual estimates of hip ROM in patients with osteoarthritis. *Physiotherapy Research International*, 5(4), 241–248. <https://doi.org/10.1002/pri.204>
- Hosseinimehr, S. H., Anbarian, M., Norasteh, A. A., Fardmal, J., & Khosravi, M. T. (2015). The comparison of scapular upward rotation and scapulohumeral rhythm between dominant and non-dominant shoulder in male overhead athletes and non-athletes. *Manual Therapy*, 20(6), 758–762. <https://doi.org/10.1016/j.math.2015.02.010>
- Hotta, G. H., Santos, A. L., McQuade, K. J., & de Oliveira, A. S. (2018). Scapular-focused exercise treatment protocol for shoulder impingement symptoms : Three-dimensional

- scapular kinematics analysis. *Clinical Biomechanics*, 51, 76–81.  
<https://doi.org/10.1016/j.clinbiomech.2017.12.005>
- Hoving, J. L., Broekhuizen, M. L. A., & Frings-Dresen, M. H. W. (2009). Return to work of breast cancer survivors: a systematic review of intervention studies. *BMC Cancer*, 9, 117.  
<https://doi.org/10.1186/1471-2407-9-117>
- Howarth, S. J., & Callaghan, J. P. (2012). Compressive force magnitude and intervertebral joint flexion/extension angle influence shear failure force magnitude in the porcine cervical spine. *Journal of Biomechanics*, 45(3), 484–490.  
<https://doi.org/10.1016/j.jbiomech.2011.11.051>
- Huang, T.-S., Ou, H.-L., & Lin, J.-J. (2019). Effects of trapezius kinesio taping on scapular kinematics and associated muscular activation in subjects with scapular dyskinesis. *Journal of Hand Therapy*, 32(3), 345–352. <https://doi.org/10.1016/j.jht.2017.10.012>
- Jang, D. H., Kim, M. W., Oh, S. J., & Kim, J. M. (2015). The influence of arm swelling duration on shoulder pathology in breast cancer patients with lymphedema. *PLoS ONE*, 10(11), 1–7.  
<https://doi.org/10.1371/journal.pone.0142950>
- Jensen, M. D., Ryan, D. H., Apovian, C. M., Ard, J. D., Comuzzie, A. G., Donato, K. A., ... Loria, C. M. (2014). 2013 AHA/ACC/TOS guideline for the management of overweight and obesity in adults: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines and The Obesity Society. *Journal of the American college of card.* *Journal of American College of Cardiology*, 129(25 Suppl 2), S102–S138. <https://doi.org/10.1161/01.cir.0000437739.71477.ee.2013>
- Johansen, J., Overgaard, J., Blichert-Toft, M., & Overgaard, M. (2000). Treatment of morbidity associated with the management of the axilla in breast-conserving therapy. *Acta Oncologica (Stockholm, Sweden)*, 39(3), 349–354. <https://doi.org/10.1080/028418600750013122>
- Johansen, S., Foss Å, K., Nesvold, I. L., Malinen, E., & Foss, S. D. (2014). Arm and shoulder morbidity following surgery and radiotherapy for breast cancer. *Acta Oncologica*, 53, 521–529. <https://doi.org/10.3109/0284186X.2014.880512>
- Johansson, K. (2005). Is physiotherapy useful to the breast cancer patient? *Acta Oncologica (Stockholm, Sweden)*, 44(5), 423–424. <https://doi.org/10.1080/02841860510029914>
- Johnson, L. J., & Miller, M. (2001). Functional testing: Approaches and injury management integration. *Work*, 16(1), 7–11. Retrieved from  
[http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list\\_uids=12441476](http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?cmd=Retrieve&db=PubMed&dopt=Citation&list_uids=12441476)
- Johnson, M. P., McClure, P. W., & Karduna, A. R. (2001). New method to assess scapular upward rotation in subjects with shoulder pathology. *The Journal of Orthopaedic and Sports Physical Therapy*, 31(2), 81–89. <https://doi.org/10.2519/jospt.2001.31.2.81>
- Karduna, A. R., McClure, P. W., Michener, L. A., & Sennett, B. (2001). Dynamic measurements of three-dimensional scapular kinematics: a validation study. *Journal of Biomechanical Engineering*, 123(2), 184. <https://doi.org/10.1115/1.1351892>
- Kärki, A., Simonen, R., Mälkiä, E., & Selfe, J. (2005). Impairments, activity limitations and

- participation restrictions 6 and 12 months after breast cancer operation. *Journal of Rehabilitation Medicine*, 37(3), 180–188. <https://doi.org/10.1080/16501970410024181>
- Keshavarz, R., Bashardoust Tajali, S., Mir, S. M., & Ashrafi, H. (2017). The role of scapular kinematics in patients with different shoulder musculoskeletal disorders: A systematic review approach. *Journal of Bodywork and Movement Therapies*, 21, 386–400. <https://doi.org/10.1016/j.jbmt.2016.09.002>
- Khadilkar, S. V., Chaudhari, C. R., Soni, G., & Bhutada, A. (2015). Is pushing the wall, the best known method for scapular winging, really the best? A Comparative analysis of various methods in neuromuscular disorders. *Journal of the Neurological Sciences*, 351(1–2), 179–183. <https://doi.org/10.1016/j.jns.2015.02.026>
- Kibler, W. (1998). The role of the scapula in athletic shoulder function. *The American Journal of Sports Medicine*, 26(2), 325–337. <https://doi.org/10.1177/03635465980260022801>
- Kibler, W., Ludewig, P. M., McClure, P. W., Michener, L. A., Bak, K., & Sciascia, A. D. (2013). Clinical implications of scapular dyskinesis in shoulder injury: the 2013 consensus statement from the “Scapular Summit”. *British Journal of Sports Medicine*, 47(14), 877–885. <https://doi.org/10.1136/bjsports-2013-092425>
- Kibler, W., & McMullen, J. (2003). Scapular dyskinesis and its relation to shoulder pain. *Journal of American Orthopaedic Surgeon*, 11, 142–151. <https://doi.org/10.1080/00140138808966731>
- Kibler, W., Uhl, T. L., Maddux, J. W. Q., Brooks, P. V., Zeller, B., & McMullen, J. (2002). Qualitative clinical evaluation of scapular dysfunction: A reliability study. *Journal of Shoulder and Elbow Surgery*, 11(6), 550–556. <https://doi.org/10.1067/mse.2002.126766>
- Kijima, T., Matsuki, K., Ochiai, N., Yamaguchi, T., Sasaki, Y., Hashimoto, E., ... Takahashi, K. (2015). In vivo 3-dimensional analysis of scapular and glenohumeral kinematics: Comparison of symptomatic or asymptomatic shoulders with rotator cuff tears and healthy shoulders. *Journal of Shoulder and Elbow Surgery*, 24(11), 1817–1826. <https://doi.org/10.1016/j.jse.2015.06.003>
- Kootstra, J. J., Dijkstra, P. U., Rietman, H., De Vries, J., Baas, P., Geertzen, J. H. B., ... Hoekstra-Weebers, J. E. H. M. (2013). A longitudinal study of shoulder and arm morbidity in breast cancer survivors 7 years after sentinel lymph node biopsy or axillary lymph node dissection. *Breast Cancer Research and Treatment*, 139(1), 125–134. <https://doi.org/10.1007/s10549-013-2509-y>
- Kootstra, J. J., Hoekstra-Weebers, J. E. H. M., Rietman, J. S., de Vries, J., Baas, P. C., Geertzen, J. H. B., & Hoekstra, H. J. (2010). A longitudinal comparison of arm morbidity in stage I-II breast cancer patients treated with sentinel lymph node biopsy, sentinel lymph node biopsy followed by completion lymph node dissection, or axillary lymph node dissection. *Annals of Surgical Oncology*, 17(9), 2384–2394. <https://doi.org/10.1245/s10434-010-0981-8>
- Kuehn, T., Klauss, W., Darsow, M., Regele, S., Flock, F., Maiterth, C., ... Kreienberg, R. (2000). Long-term morbidity following axillary dissection in breast cancer patients--clinical assessment, significance for life quality and the impact of demographic, oncologic and therapeutic factors. *Breast Cancer Research & Treatment*, 64(3), 275–286.

- Lacomba, M. T. F. (2010). Effectiveness of early physiotherapy to prevent lymphoedema after surgery for breast cancer: Randomised, single blinded, clinical trial. *British Medical Journal*, 21(3), 220–221. [https://doi.org/10.1016/S1043-321X\(10\)79563-1](https://doi.org/10.1016/S1043-321X(10)79563-1)
- Lafayette Instrument. (1998). The Minnesota Dexterity Test Examiners Manual.
- Lafayette Instrument. (2002). Purdue Pegboard Test.
- Lang, A. E., & Dickerson, C. R. (2017a). Normative kinematics of reaching and dexterity tasks: moving towards a quantitative baseline for Functional Capacity Evaluations (FCEs). *International Biomechanics*, 4(2), 37–49. <https://doi.org/10.1080/23335432.2017.1326843>
- Lang, A. E., & Dickerson, C. R. (2017b). Task intensity influences upper limb and torso kinematics during two common overhead Functional Capacity Evaluation tasks. *Work*, 58(2), 121–134.
- Lang, A. E., Dickerson, C. R., Kim, S. Y., Stobart, J., & Milosavljevic, S. (2019). Impingement pain affects kinematics of breast cancer survivors in work- related functional tasks. *Clinical Biomechanics*, 70(January), 223–230. <https://doi.org/10.1016/j.clinbiomech.2019.10.001>
- Lang, A. E., Kim, S. Y., Milosavljevic, S., & Dickerson, C. R. (2019). The utility of the acromion marker cluster (AMC) in a clinical population. *Journal of Electromyography and Kinesiology*. <https://doi.org/10.1016/j.jelekin.2019.04.002>
- Lang, A. E., & Milosavljevic, S. (2019). Visual estimation of shoulder posture : accuracy and reliability across five planes of motion. *Physical Therapy Reviews*, 24(3–4), 118–124. <https://doi.org/10.1080/10833196.2019.1637594>
- Lang, A. E., Murphy, M., Dickerson, C. R., Stavness, I., & Kim, S. Y. (n.d.). Factors related to shoulder dysfunction in breast cancer survivors. *Rehabilitation Oncology*.
- Lauridsen, M. C., Tørsleff, K. R., Husted, H., & Erichsen, C. (2000). Physiotherapy treatment of late symptoms following surgical treatment of breast cancer. *Breast (Edinburgh, Scotland)*, 9(1), 45–51. <https://doi.org/10.1054/brst.1999.0087>
- Lawrence, R. L., Braman, J. P., & Ludewig, P. M. (2019). The Impact of Decreased Scapulothoracic Upward Rotation on Subacromial Proximities. *Journal of Orthopaedic and Sports Physical Therapy*, 49(3), 180–192. <https://doi.org/10.2519/jospt.2019.8590>
- Lee, C. H., Chung, S. Y., Kim, W. Y., & Yang, S. N. (2019). Effect of breast cancer surgery on chest tightness and upper limb dysfunction. *Medicine*, 98(19), e15524. <https://doi.org/https://dx.doi.org/10.1097/MD.00000000000015524>
- Lee, S., Yang, D., Kim, H., & Choy, W. (2013). A comparison of 3D scapular kinematics between dominant and nondominant shoulders during multiplanar arm motion. *Indian Journal of Orthopaedics*, 47(2), 135. <https://doi.org/10.4103/0019-5413.108882>
- Leidenius, M., Leppänen, E., Krogerus, L., & Von Smitten, K. (2003). Motion restriction and axillary web syndrome after sentinel node biopsy and axillary clearance in breast cancer. *American Journal of Surgery*, 185(2), 127–130. [https://doi.org/10.1016/S0002-9610\(02\)01214-X](https://doi.org/10.1016/S0002-9610(02)01214-X)

- Lemieux, P. O., Nuno, N., Hagemeister, N., Tetreault, P., Nuño, N., Hagemeister, N., & Tetreault, P. (2012). Mechanical analysis of cuff tear arthropathy during multiplanar elevation with the AnyBody shoulder model. *Clinical Biomechanics*, 27(8), 801–806. <https://doi.org/10.1016/j.clinbiomech.2012.04.008>
- Leong, H. T., Ng, G. Y. fat, Chan, S. C., & Fu, S. N. (2017). Rotator cuff tendinopathy alters the muscle activity onset and kinematics of scapula. *Journal of Electromyography and Kinesiology*, 35, 40–46. <https://doi.org/10.1016/j.jelekin.2017.05.009>
- Levy, E. W., Pfalzer, L. A., Danoff, J., Springer, B. A., McGarvey, C., Shieh, C. Y., ... Stout, N. L. (2012). Predictors of functional shoulder recovery at 1 and 12 months after breast cancer surgery. *Breast Cancer Research and Treatment*, 134(1), 315–324. <https://doi.org/10.1007/s10549-012-2061-1>
- Lin, J.-J., Kim, H. K., & Yang, J.-L. (2006). Effect of shoulder tightness on glenohumeral translation, scapular kinematics, and scapulohumeral rhythm in subjects with stiff shoulders. *Journal of Orthopaedic Research*, 1044–1051. <https://doi.org/10.1002/jor>
- Lindstroem, R., Graven-Nielsen, T., & Falla, D. (2012). Current pain and fear of pain contribute to reduced maximum voluntary contraction of neck muscles in patients with chronic neck pain. *Archives of Physical Medicine & Rehabilitation*, 93, 2042–2048. <https://doi.org/10.1016/j.apmr.2012.04.014>
- Lomond, K. V., & Côté, J. N. (2011). Differences in posture-movement changes induced by repetitive arm motion in healthy and shoulder-injured individuals. *Clinical Biomechanics*, 26(2), 123–129. <https://doi.org/10.1016/j.clinbiomech.2010.09.012>
- Ludewig, P. M., & Cook, T. M. (2000). Alterations in shoulder kinematics and associated muscle activity in people with symptoms of shoulder impingement. *Physical Therapy*, 80(3), 276–291.
- Ludewig, P. M., Phadke, V., Braman, J. P., Hassett, D. R., Cieminski, C. J., & Laprade, R. F. (2009). Motion of the shoulder complex during multiplanar humeral elevation. *Journal of Bone and Joint Surgery*, 91-A(2), 378–389. <https://doi.org/10.2106/JBJS.G.01483>
- Ludewig, P. M., & Reynolds, J. F. (2009). The association of scapular kinematics and glenohumeral joint pathologies. *The Journal of Orthopaedic and Sports Physical Therapy*, 39(2), 90–104. <https://doi.org/10.2519/jospt.2009.2808>
- Lukasiewicz, A. C., McClure, P., Lori Michener, O., Praff, N., & Senneff, B. (1999). Comparison of 3-dimensional scapular position and orientation between -subjects with and without shoulder impingement. *Journal of Orthopaedic & Sports Physical Therapy*, 29(10), 574–586.
- Maclean, K. F. E., Chopp, J. N., Grewal, T., Picco, B. R., & Dickerson, C. R. (2014). Three-dimensional comparison of static and dynamic scapular motion tracking techniques. *Journal of Electromyography and Kinesiology*, 24(1), 65–71. <https://doi.org/10.1016/j.jelekin.2013.09.011>
- Mathiassen, S. E., Möller, T., & Forsman, M. (2003). Variability in mechanical exposure within and between individuals performing a highly constrained industrial work task. *Ergonomics*,

- 46(8), 800–824. <https://doi.org/10.1080/0014013031000090125>
- Matsuki, K., Matsuki, K. O., Mu, S., Yamaguchi, S., Ochiai, N., Sasho, T., ... Banks, S. A. (2011). In vivo 3-dimensional analysis of scapular kinematics: Comparison of dominant and nondominant shoulders. *Journal of Shoulder and Elbow Surgery*, 20(4), 659–665. <https://doi.org/10.1016/j.jse.2010.09.012>
- Maunsell, E., Brisson, J., & Deschênes, L. (1993). Arm problems and psychological distress after surgery for breast cancer. *Canadian Journal of Surgery. Journal Canadien de Chirurgie*, 36(4), 315–320. Retrieved from <http://europepmc.org/abstract/MED/8370012>
- McClure, P. W., Michener, L. A., & Karduna, A. R. (2006). Shoulder function and 3-dimensional scapular kinematics in people with and without shoulder impingement syndrome. *Physical Therapy*, 86(8), 1075–1090. [https://doi.org/10.1016/s0268-0033\(03\)00047-0](https://doi.org/10.1016/s0268-0033(03)00047-0)
- McClure, P. W., Michener, L. A., Sennett, B. J., & Karduna, A. R. (2001). Direct 3-dimensional measurement of scapular kinematics during dynamic movements in vivo. *Journal of Shoulder and Elbow Surgery*, 10(3), 269–277. <https://doi.org/10.1067/mse.2001.112954>
- McClure, P. W., Tate, A. R., Kareha, S., Irwin, D., & Zlupko, E. (2009). A clinical method for identifying scapular dyskinesis, part 1: Reliability. *Journal of Athletic Training*, 44(2), 160–164. <https://doi.org/10.4085/1062-6050-44.2.160>
- McFarland, E. G., Garzon-Muvdi, J., Jia, X., Desai, P., & Petersen, S. a. (2010). Clinical and diagnostic tests for shoulder disorders: A critical review. *British Journal of Sports Medicine*, 44(5), 328–332. <https://doi.org/10.1136/bjsm.2009.067314>
- McNeely, M. L., Campbell, K., Ospina, M., Rowe, B. H., Dabbs, K., Klassen, T. P., ... Courneya, K. (2010). Exercise interventions for upper-limb dysfunction due to breast cancer treatment. *Cochrane Database of Systematic Reviews*, (6). <https://doi.org/10.1002/14651858.CD005211.pub2>
- Meskers, C. G. M., van de Sande, M. A. J., & de Groot, J. H. (2007). Comparison between tripod and skin-fixed recording of scapular motion. *Journal of Biomechanics*, 40(4), 941–946. <https://doi.org/10.1016/j.jbiomech.2006.02.011>
- Meskers, C. G. M., Vermeulen, H. M., De Groot, J. H., Van Der Helm, F. C. T., & Rozing, P. M. (1998). 3D shoulder position measurements using a six-degree-of-freedom electromagnetic tracking device. *Clinical Biomechanics*, 13(4–5), 280–292. [https://doi.org/10.1016/S0268-0033\(98\)00095-3](https://doi.org/10.1016/S0268-0033(98)00095-3)
- Miaskowski, C., Paul, S. M., Cooper, B., West, C., Levine, J. D., Elboim, C., ... Aouizerat, B. E. (2014). Identification of patient subgroups and risk factors for persistent arm/shoulder pain following breast cancer surgery. *European Journal of Oncology Nursing*, 18(3), 242–253. <https://doi.org/10.1016/j.ejon.2013.12.002>
- Michener, L. A., McClure, P. W., & Karduna, A. R. (2003). Anatomical and biomechanical mechanisms of subacromial impingement syndrome. *Clinical Biomechanics*, 18(5), 369–379. [https://doi.org/10.1016/S0268-0033\(03\)00047-0](https://doi.org/10.1016/S0268-0033(03)00047-0)
- Miedema, B., Hamilton, R., Tatemichi, S., Thomas-Maclean, R., Towers, A., Hack, T. F., ...

- Kwan, W. (2008). Predicting recreational difficulties and decreased leisure activities in women 6-12 months post breast cancer surgery. *Journal of Cancer Survivorship*, 2(4), 262–268. <https://doi.org/10.1007/s11764-008-0068-8>
- Milgrom, C., Schaffler, M., Gilbert, S., & van Holsbeeck, M. (1995). Rotator-cuff changes in asymptomatic adults. The effect of age, hand dominance and gender. *The Journal of Bone and Joint Surgery*, 77(2), 296–298.
- Mitchell, C., Adebajo, A., Hay, E., & Carr, A. (2005). Shoulder pain: diagnosis and management in primary care Sources and selection criteria. *BMJ Clinical Review*, 351, 1124–1128.
- Moen, M. H., de Vos, R.-J., Ellenbecker, T. S., & Weir, A. (2010). Clinical tests in shoulder examination: How to perform them. *British Journal of Sports Medicine*, 44(5), 370–375. <https://doi.org/10.1136/bjsm.2010.071928>
- Morais, N. V., & Pascoal, A. (2013). Scapular positioning assessment: Is side-to-side comparison clinically acceptable? *Manual Therapy*, 18, 46–53. <https://doi.org/10.1016/j.math.2012.07.001>
- Muscolino, G., Leo, E., Sacchini, V., Bedini, A. V., & Luini, A. (1988). Resectable breast cancer: axillary dissection sparing pectoralis muscles and nerves. *European Journal of Surgical Oncology : The Journal of the European Society of Surgical Oncology and the British Association of Surgical Oncology*, 14(5), 429–433. Retrieved from <http://europepmc.org/abstract/MED/3181447>
- Nesvold, I.-L., Dahl, A. A., Løkkevik, E., Mengshoel, A. M., & Fosså, S. D. (2008). Arm and shoulder morbidity in breast cancer patients after breast-conserving therapy versus mastectomy. *Acta Oncologica*, 47(5), 835–842. <https://doi.org/10.1080/02841860801961257>
- Nesvold, I. L., Reinertsen, K. V., Fossa, S. D., & Dahl, A. A. (2011). The relation between arm/shoulder problems and quality of life in breast cancer survivors: a cross-sectional and longitudinal study. *Journal of Cancer Survivorship : Research and Practice*, 5(1), 62–72. <https://doi.org/10.1007/s11764-010-0156-4>
- Nijs, J., Roussel, N., Struyf, F., Mottram, S., & Meeusen, R. (2007). Clinical Assessment of Scapular Positioning in Patients with Shoulder Pain: State of the Art. *Journal of Manipulative and Physiological Therapeutics*, 30(1), 69–75. <https://doi.org/10.1016/j.jmpt.2006.11.012>
- Nijs, J., Roussel, N., Vermeulen, K., & Souvereinys, G. (2005). Scapular positioning in patients with shoulder pain: A study examining the reliability and clinical importance of 3 clinical tests. *Archives of Physical Medicine and Rehabilitation*, 86(7), 1349–1355. <https://doi.org/10.1016/j.apmr.2005.03.021>
- Nitkin, P., & Schultz, I. Z. (2011). Cancer and Work : A Canadian Perspective, (January).
- Nussbaum, M. a, & Zhang, X. (2000). Heuristics for locating upper extremity joint centres from a reduced set of surface markers. *Human Movement Science*, 19(5), 797–816. [https://doi.org/10.1016/S0167-9457\(00\)00020-8](https://doi.org/10.1016/S0167-9457(00)00020-8)
- Odom, C. J., Taylor, a B., Hurd, C. E., & Denegar, C. R. (2001). Measurement of scapular



- asymmetry and assessment of shoulder dysfunction using the Lateral Scapular Slide Test: a reliability and validity study. *Physical Therapy*, 81(2), 799–809.  
<https://doi.org/10.1177/036354659202000206>
- Oyama, S., Atc, À., Myers, J. B., Atc, À., Wassinger, C. A., Ricci, R. D., & Lephart, S. M. (2008). Asymmetric resting scapular posture in healthy overhead athletes. *Journal of Athletic Training*, 43(6), 565–570.
- Paine, R. M., & Voight, M. (2013). The Role of the Scapula. *International Journal of Sports Physical Therapy*, 5(1), 617–629. <https://doi.org/10.2519/jospt.1993.18.1.386>
- Patey, D. H., & Dyson, W. H. (1948). The prognosis of carcinoma of the breast in relation to the type of operation performed. *British Journal of Cancer*, 2(1), 7–13.  
<https://doi.org/10.1038/bjc.1948.2>
- Peters, M. (1998). Prolonged practice of a simple motor task by preferred and nonpreferred hands. *Journal of Motor Behaviour*, 3(1), 77–96.
- Phadke, V., Braman, J. P., LaPrade, R. F., & Ludewig, P. M. (2011). Comparison of glenohumeral motion using different rotation sequences. *Journal of Biomechanics*, 44(4), 700–705. <https://doi.org/10.1016/j.jbiomech.2010.10.042>
- Phadke, V., Camargo, P. R., & Ludewig, P. M. (2009). Scapular and rotator cuff muscle activity during arm elevation: A review of normal function and alterations with shoulder impingement. *Revista Brasileira de Fisioterapia*, 13(1), 1–9. <https://doi.org/10.1590/S1413-35552009005000012>
- Pinto, M., Gimigliano, F., Tatengelo, F., Megna, M., Izzo, F., Gimigliano, R., & Iolascon, G. (2013). Upper limb function and quality of life in breast cancer related lymphedema: a cross sectional study. *European Journal of Physical and Rehabilitation Medicine*, 48, 1–9.
- Rapp, E. A., Richardson, R. T., Russo, S. A., Rose, W. C., & Richards, J. G. (2017). A comparison of two non-invasive methods for measuring scapular orientation in functional positions. *Journal of Biomechanics*, 61, 269–274.  
<https://doi.org/10.1016/j.jbiomech.2017.07.032>
- Reneman, M. F., Soer, R., & Gerrits, E. H. J. (2005). Basis for an FCE methodology for patients with work-related upper limb disorders. *Journal of Occupational Rehabilitation*, 15(3), 353–363. <https://doi.org/10.1007/s10926-005-5942-x>
- Ribeiro, I. L., Camargo, P. R., Albuquerque-sendín, F., Ferraari, A. V., Arrais, C. R., & Salvini, T. F. (2019). Three-dimensional scapular kinematics , shoulder outcome measures and quality of life following treatment for breast cancer – A case control study. *Musculoskeletal Science and Practice*, 40, 72–79. <https://doi.org/10.1016/j.msksp.2019.01.012>
- Rietman, J. ., Dijkstra, P. ., Hoekstra, H. ., Eisma, W. ., Szabo, B. ., Groothoff, J. ., & Geertzen, J. H. . (2003). Late morbidity after treatment of breast cancer in relation to daily activities and quality of life: a systematic review. *European Journal of Surgical Oncology (EJSO)*, 29(3), 229–238. <https://doi.org/10.1053/ejso.2002.1403>
- Rietman, J. S., Dijkstra, P. U., Debreczeni, R., Geertzen, J. H. B., Robinson, D. P. H., & De Vries, J. (2004). Impairments, disabilities and health related quality of life after treatment

- for breast cancer: a follow-up study 2.7 years after surgery. *Disability and Rehabilitation*, 26(April 2016), 78–84. <https://doi.org/10.1080/09638280310001629642>
- Rietman, J. S., Geertzen, J. H. B., Hoekstra, H. J., Baas, P., Dolsma, W. V., de Vries, J., ... Dijkstra, P. U. (2006). Long term treatment related upper limb morbidity and quality of life after sentinel lymph node biopsy for stage I or II breast cancer. *European Journal of Surgical Oncology*, 32(2), 148–152. <https://doi.org/10.1016/j.ejso.2005.11.008>
- Robert-Lachaine, X., Allard, P., Godbout, V., Tétreault, P., & Begon, M. (2016). Scapulohumeral rhythm relative to active range of motion in patients with symptomatic rotator cuff tears. *Journal of Shoulder and Elbow Surgery*, 25(10), 1616–1622. <https://doi.org/10.1016/j.jse.2016.02.031>
- Roren, A., Nguyen, C., Palazzo, C., Fayad, F., Revel, M., Gregory, T., ... Lefèvre-Colau, M. M. (2017). Kinematic analysis of the shoulder complex after anatomic and reverse total shoulder arthroplasty: A cross-sectional study. *Musculoskeletal Science and Practice*, 29, 84–90. <https://doi.org/10.1016/j.msksp.2017.03.006>
- Roy, J. S., Moffet, H., & McFadyen, B. J. (2008). Upper limb motor strategies in persons with and without shoulder impingement syndrome across different speeds of movement. *Clinical Biomechanics*, 23(10), 1227–1236. <https://doi.org/10.1016/j.clinbiomech.2008.07.009>
- Sagen, A., Kaaresen, R., Sandvik, L., Thune, I., & Risberg, M. A. (2014). Upper limb physical function and adverse effects after breast cancer surgery: A prospective 2.5-year follow-up study and preoperative measures. *Archives of Physical Medicine and Rehabilitation*, 95(5), 875–881. <https://doi.org/http://dx.doi.org/10.1016/j.apmr.2013.12.015>
- Sagen, A., Karesen, R., Sandvik, L., Risberg, M. A., Sagen, A., Karesen, R., ... Risberg, M. A. (2009). Changes in arm morbidities and health-related quality of life after breast cancer surgery: a five-year follow-up study. *Acta Oncologica*, 48(8), 1111–1118. <https://doi.org/10.3109/02841860903061691>
- Schmidt-Ullrich, R., Wazer, D. E., Safaii, H., Tercilla, O., Marchant, D. J., Smith, T. J., ... Robert, N. J. (1989). Tumor margin assessment as a guide to optimal conservation surgery and irradiation in early stage breast carcinoma. *International Journal of Radiation Oncology, Biology, Physics*, 17(4), 733–738. [https://doi.org/10.1016/0360-3016\(89\)90059-X](https://doi.org/10.1016/0360-3016(89)90059-X)
- Schwartz, C., Croisier, J.-L., Rigaux, E., Denoel, V., Bruls, O., & Forthomme, B. (2014). Dominance effect on scapula 3-dimensional posture and kinematics in healthy male and female populations. *Journal of Shoulder and Elbow Surgery*, 23, 873–881. <https://doi.org/10.1016/j.jse.2013.08.020>
- Seaman, F. A., Albert, W. J., Weldon, N. R. E., Croll, J., & Callaghan, J. P. (2010). Biomechanical shoulder loads and postures in light automotive assembly workers: Comparison between shoulder pain/no pain groups. *Work*, 35(1), 39–48. <https://doi.org/10.3233/WOR-2010-0956>
- Seitz, A. L., McClure, P. W., Finucane, S., Boardman, N. D., & Michener, L. A. (2011). Clinical Biomechanics Mechanisms of rotator cuff tendinopathy : Intrinsic , extrinsic , or both ? *Clinical Biomechanics*, 26, 1–12. <https://doi.org/10.1016/j.clinbiomech.2010.08.001>

- Shamley, D. R., Lascrain-Aguirrebeña, I., Oskrochi, R., & Srinaganathan, R. (2012). Shoulder morbidity after treatment for breast cancer is bilateral and greater after mastectomy. *Acta Oncologica*, 51(8), 1045–1053. <https://doi.org/10.3109/0284186X.2012.695087>
- Shamley, D. R., Srinaganathan, R., Oskrochi, R., Lascrain-Aguirrebeña, I., & Sugden, E. (2008). Three-dimensional scapulothoracic motion following treatment for breast cancer. *Breast Cancer Research and Treatment*, 118(2), 315–322. <https://doi.org/10.1007/s10549-008-0240-x>
- Shamley, D. R., Srinaganathan, R., Weatherall, R., Oskrochi, R., Watson, M., Ostlere, S., & Sugden, E. (2007). Changes in shoulder muscle size and activity following treatment for breast cancer. *Breast Cancer Research and Treatment*, 106(1), 19–27. <https://doi.org/10.1007/s10549-006-9466-7>
- Short, P. F., Vasey, J. J., & Tunceli, K. (2005). Employment pathways in a large cohort of adult cancer survivors. *Cancer*, 103(6), 1292–1301. <https://doi.org/10.1002/cncr.20912>
- Soer, R., van der Schans, C. P., Geertzen, J. H., Groothoff, J. W., Brouwer, S., Dijkstra, P. U., & Reneman, M. F. (2009). Normative Values for a Functional Capacity Evaluation. *Archives of Physical Medicine and Rehabilitation*, 90(10), 1785–1794. <https://doi.org/10.1016/j.apmr.2009.05.008>
- Solem-Bertoft, E., Thuomas, K.-A., & Westerberg, C.-E. (1993). The influence of scapular retraction and protraction on the width of the subacromial space. An MRI study. *Clinical Orthopaedics and Related Research*, (296), 99–103. <https://doi.org/0009-921X>
- Soulen, R. L., Romero, J. A., Chuba, P. J., Evelhoch, J. L., Simpson, R. E., & Forman, J. D. (1997). Musculoskeletal complications of neutron therapy for prostate cancer. *Radiation Oncology Investigations*, 5(2), 81–91. [https://doi.org/10.1002/\(SICI\)1520-6823\(1997\)5:2<81::AID-ROI6>3.0.CO;2-F](https://doi.org/10.1002/(SICI)1520-6823(1997)5:2<81::AID-ROI6>3.0.CO;2-F)
- Spelten, E. R., Sprangers, M. A. G., & Verbeek, J. H. A. M. (2002). Factors reported to influence the return to work of cancer survivors: A literature review. *Psycho-Oncology*, 11(2), 124–131. <https://doi.org/10.1002/pon.585>
- Spinelli, B. A., Silfies, S., Jacobs, L. A., Brooks, A. D., & Ebaugh, D. (2016). Scapulothoracic and glenohumeral motions during functional reaching tasks in women with a history of breast cancer and healthy age-matched controls. *Rehabilitation Oncology*, 34(4), 127–136. <https://doi.org/10.1097/01.REO.0000000000000033>
- Steiner, J. F., Cavender, T. A., Main, D. S., & Bradley, C. J. (2004). Assessing the impact of cancer on work outcomes: What are the research needs? *Cancer*, 101(8), 1703–1711. <https://doi.org/10.1002/cncr.20564>
- Stout, N. L., Silver, J. K., Raj, V. S., Campbell, G., Hendricks, J., Perkin, K., & Chan, L. (2016). Toward a National Initiative in Cancer Rehabilitation: Recommendations From a Subject Matter Expert Group Toward a National Initiative in Cancer Rehabilitation : Recommendations From a Subject Matter Expert Group. *Archives of Physical Medicine and Rehabilitation*, 9(11), 2006–2015. <https://doi.org/10.1016/j.apmr.2016.05.002>
- Struyf, F., Nijs, J., Mottram, S., Roussel, N. a, Cools, A. M. J., & Meeusen, R. (2012). Clinical

- assessment of the scapula: a review of the literature. *British Journal of Sports Medicine*, 48(11), 883–890. <https://doi.org/10.1136/bjsports-2012-091059>
- Stubblefield, M. D., & Keole, N. (2014). Upper body pain and functional disorders in patients with breast cancer. *Physical Medicine and Rehabilitation*, 6(2), 170–183. <https://doi.org/10.1016/j.pmrj.2013.08.605>
- Sugden, E. M., Rezvani, M., Harrison, J. M., & Hughes, L. K. (1998). Shoulder movement after treatment of early stage breast cancer. *Clinical Oncology*, 10, 173–181.
- Tempelhof, S., Rupp, S., & Seil, R. (1999). Age-related prevalence of rotator cuff tears in asymptomatic shoulders. *Journal of Shoulder and Elbow Surgery*, 8(4), 296–299. [https://doi.org/10.1016/S1058-2746\(99\)90148-9](https://doi.org/10.1016/S1058-2746(99)90148-9)
- Todor, J. I., Kyprie, P. M., & Price, L. (1982). Lateral asymmetries in arm, wrist and finger movements. *Cortex*, 18(4), 515–523.
- Trippolini, M. A., Dijkstra, P. U., Jansen, B., Oesch, P., Geertzen, J. H. B., & Reneman, M. F. (2014). Reliability of clinician rated physical effort determination during functional capacity evaluation in patients with chronic musculoskeletal pain. *Journal of Occupational Rehabilitation*, 24(2), 361–369. <https://doi.org/10.1007/s10926-013-9470-9>
- Turgut, E., Duzgun, I., & Baltaci, G. (2016). Scapular asymmetry in participants with and without shoulder impingement syndrome ; a three-dimensional motion analysis. *Clinical Biomechanics*, 39, 1–8. <https://doi.org/10.1016/j.clinbiomech.2016.09.001>
- Turgut, E., Pedersen, Ø., Duzgun, I., & Baltaci, G. (2016). Three-dimensional scapular kinematics during open and closed kinetic chain movements in asymptomatic and symptomatic subjects. *Journal of Biomechanics*, 49(13), 2770–2777. <https://doi.org/10.1016/j.jbiomech.2016.06.015>
- Ueda, Y., Tanaka, H., Morioka, S., Tachibana, T., Hayashi, T., Ichihashi, N., ... Nobuhara, K. (2019). Clinical Biomechanics Comparison of scapular upward rotation during arm elevation in the scapular plane in healthy volunteers and patients with rotator cuff tears pre-. *Clinical Biomechanics*, 63(March), 207–213. <https://doi.org/10.1016/j.clinbiomech.2019.03.012>
- Uhl, T. L., Kibler, W. B., Gecewich, B., & Tripp, B. L. (2009). Evaluation of clinical assessment methods for scapular dyskinesis. *Arthroscopy : The Journal of Arthroscopic & Related Surgery : Official Publication of the Arthroscopy Association of North America and the International Arthroscopy Association*, 25(11), 1240–1248. <https://doi.org/10.1016/j.arthro.2009.06.007>
- van Andel, C., van Hutten, K., Eversdijk, M., Veeger, D., & Harlaar, J. (2009). Recording scapular motion using an acromion marker cluster. *Gait and Posture*, 29(1), 123–128. <https://doi.org/10.1016/j.gaitpost.2008.07.012>
- Verbelen, H., Gebruers, N., Eeckhout, F.-M., Verlinden, K., & Tjalma, W. (2014). Shoulder and arm morbidity in sentinel node-negative breast cancer patients: a systematic review. *Breast Cancer Research and Treatment*, 144(1), 21–31. <https://doi.org/10.1007/s10549-014-2846-5>

- Verbelen, H., Tjalma, W., Meirte, J., & Gebruers, N. (2019). Long-term morbidity after a negative sentinel node in breast cancer patients. *European Journal of Cancer Care*, e13077. <https://doi.org/10.1111/ecc.13077>
- Voogd, A. C., Ververs, J. M. M. A., Vingerhoets, A. J. J. M., Roumen, R. M. H., Coebergh, J. W. W., & Crommelin, M. A. (2003). Lymphoedema and reduced shoulder function as indicators of quality of life after axillary lymph node dissection for invasive breast cancer. *British Journal of Surgery*, 90(1), 76–81. <https://doi.org/10.1002/bjs.4010>
- Walker, D., Matsuki, K., Struk, A. M., Wright, T. W., & Banks, S. A. (2015). Scapulohumeral rhythm in shoulders with reverse shoulder arthroplasty. *Journal of Shoulder and Elbow Surgery*, 24(7), 1129–1134. <https://doi.org/10.1016/j.jse.2014.11.043>
- Warner, M. B., Chappell, P. H., & Stokes, M. J. (2012). Measuring scapular kinematics during arm lowering using the acromion marker cluster. *Human Movement Science*, 31(2), 386–396. <https://doi.org/10.1016/j.humov.2011.07.004>
- Watkins, M., Riddle, D., & Lamb, R. (1991). Reliability of goniometric and visual estimates of knee range of motion obtained in a clinical setting. *Physical Therapy*, 71, 90–97.
- Watson, L., Balster, S. M., Finch, C., & Dalziel, R. (2005). Measurement of scapula upward rotation: a reliable clinical procedure. *British Journal of Sports Medicine*, 39(9), 599–603. <https://doi.org/10.1136/bjsm.2004.013243>
- Wedgwood, K., & Benson, E. (1992). Non-tumour morbidity and mortality after modified radical mastectomy. *Annals of the Royal College of Surgeons of England*, 74(5), 314–317. Retrieved from <http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2497641/>
- Wennman-Larsen, A., Alexanderson, K., Olsson, M., Nilsson, M. I., & Petersson, L. M. (2013). Sickness absence in relation to breast and arm symptoms shortly after breast cancer surgery. *Breast*, 22(5), 767–772. <https://doi.org/10.1016/j.breast.2013.01.006>
- Wernicke, A. G., Shamis, M., Sidhu, K. K., Turner, B. C., Goltser, Y., Khan, I., ... Komarnicky-Kocher, L. T. (2013). Complication rates in patients with negative axillary nodes 10 years after local breast radiotherapy after either sentinel lymph node dissection or axillary clearance. *American Journal of Clinical Oncology*, 36(1), 12–19. <https://doi.org/10.1097/COC.0b013e3182354bda>
- Williams, J. G., & Callaghan, M. (1990). Comparison of Visual Estimation and Goniometry in Determination of a Shoulder Joint Angle. *Physiotherapy*, 76(10), 655–657. [https://doi.org/10.1016/S0031-9406\(10\)63103-3](https://doi.org/10.1016/S0031-9406(10)63103-3)
- Winter, D. A. (2009). *Biomechanics and Motor Control of Human Movement* (4th ed.). Hoboken, New Jersey, New Jersey: John Wiley & Sons.
- Wu, G., Van Der Helm, F. C. T., Veeger, H. E. J., Makhsous, M., Van Roy, P., Anglin, C., ... Buchholz, B. (2005). ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. *Journal of Biomechanics*, 38(5), 981–992. <https://doi.org/10.1016/j.jbiomech.2004.05.042>
- Wu, W., Lee, P. V. S., & Ackland, D. C. (2017). The sensitivity of shoulder muscle and joint

force predictions to changes in joint kinematics: A Monte-Carlo analysis. *Gait and Posture*, 54, 87–92. <https://doi.org/10.1016/j.gaitpost.2017.02.027>

Yamaguchi, K., Sher, J. S., Andersen, W. K., Garretson, R., Uribe, J. W., Hechtman, K., & Neviaser, R. J. (2000). Glenohumeral motion in patients with rotator cuff tears: A comparison of asymptomatic and symptomatic shoulders. *Journal of Shoulder and Elbow Surgery*, 9(1), 6–11. [https://doi.org/10.1016/S1058-2746\(00\)90002-8](https://doi.org/10.1016/S1058-2746(00)90002-8)

Yang, E. J., Park, W. B., Seo, K. S., Kim, S. W., Heo, C. Y., & Lim, J. Y. (2010). Longitudinal change of treatment-related upper limb dysfunction and its impact on late dysfunction in breast cancer survivors: A prospective cohort study. *Journal of Surgical Oncology*, 101(1), 84–91. <https://doi.org/10.1002/jso.21435>

## APPENDIX A: LETTERS OF COPYRIGHT PERMISSON

Permission letter from Elsevier to include content published in the *Journal of Electromyography and Kinesiology* and *Clinical Biomechanics* (Chapters 3 & 4).

Dear Ms. Angelica E. Lang,

Article reference: JJEK2298

Thank you for your query regarding using your article in your thesis.

I can confirm that that authors can use their articles, in full or in part, for a wide range of scholarly, non-commercial purposes one of which is inclusion in a thesis or dissertation. See the following link for further information on this

<https://www.elsevier.com/about/our-business/policies/copyright/personal-use>

As you will be able to see from the above link, our policy is to allow authors to use their work in their thesis or dissertation (provided that this is not to be published commercially).

Therefore, I can confirm that you can make it publicly available on your university web site/repository for non- commercial use.

If you require further clarification, please contact [permissions@elsevier.com](mailto:permissions@elsevier.com) who will be able to help.

Kind regards,

**Rommel Buenasflores Jallorina**  
Researcher Support  
**ELSEVIER**

Permission letter from Canadian Cancer Society to include figures from their website (Figures 1-3, Chapter 2).

Hello Angelica,

Thank you for contacting the Canadian Cancer Society; as far as I can tell; utilizing the information and images on our website for educational purposes should not be a problem. You can read more about our terms and conditions regarding copyright permission [here](#).

If you have any other questions, please feel free to contact our Cancer Information Service at 1 888 939-3333. We are available Monday to Friday from 9am to 7pm (Eastern Standard Time).

Sincerely,  
Elliott, CIPS

The information contained in or attached to this email is intended only for the use of the individual or entity to which it is addressed. If you are not the intended recipient, or a person responsible for delivering it to the intended recipient, you are not authorized to and must not disclose, copy, distribute, or retain this message or any part of it. The Canadian Cancer Society is committed to adhere to privacy and consent policies that safeguard collection and storage of personal information ([Privacy policy](#)). The Canadian Cancer Society strives to provide evidence based information about cancer related topics. We encourage you to discuss all information with your health care professional ([Medical disclaimer](#)).



## APPENDIX B: INFORMATION AND CONSENT FORM



### PARTICIPANT INFORMATION AND CONSENT FORM

#### Study Title:

Towards improved clinical evaluation of the shoulder: defining upper limb motion of breast cancer survivors during functional evaluation tasks

#### Research Team:

##### Student investigator:

##### Angelica Lang

University of Saskatchewan  
Department of Health Sciences  
e-mail: angelica.lang@usask.ca

##### Faculty Supervisors:

##### Dr. Stephan Milosavljevic, Ph. D.

University of Saskatchewan  
School of Physical Therapy  
Phone: 306-966-8655  
Email: Stephan.milosavljevic@usask.ca

##### Dr. Soo Kim, Ph.D.

University of Saskatchewan  
School of Physical Therapy  
Phone: 306-966-8399  
Email: soo.kim@usask.ca

##### Dr. Clark R. Dickerson, Ph. D.

University of Waterloo  
Department of Kinesiology  
Phone: 1-519-888-4567 ext: 37844  
Email: clark.dickerson@uwaterloo.ca

## 1. INTRODUCTION

Thank you for expressing an interest in this research. You are invited to take part in this research study because you are an adult female between the ages of 35 and 65, have received treatment (unilateral or bilateral mastectomy) for breast cancer at least 6 months ago OR have a symptomatic rotator cuff tendinopathy OR have no upper limb limitations. Your participation is voluntary. It is up

to you to decide whether or not you wish to take part. If you wish to participate, you will be asked to sign the consent form on the last page.

## **2. WHO IS CONDUCTING THE STUDY**

The study is being conducted by a team of researchers within the Department of Health Sciences, led by Drs. Milosavljevic, for Angelica Lang's PhD thesis. Neither the institution nor any of the investigators / research team will receive any direct financial benefit from conducting this study.

## **3. PURPOSE OF THE STUDY**

This goal of this study is to define kinematics, or motion, of breast cancer survivors during a range of clinically and functionally relevant shoulder-centre tasks. These measured kinematics of breast cancer survivors will be compared to kinematics of non-cancer controls and a rotator cuff injury group to determine the presence of alterations and to help to identify if the alterations are similar to those displayed with rotator cuff injury. This information will enhance the understanding of shoulder movement following breast cancer surgery, particularly for functional, work-related tasks. This will allow for more specific recommendations for clinicians regarding treatment, rehabilitation, and return to work recommendations. This study is a part of Angelica Lang's PhD project.

## **4. INCLUSION/EXCLUSION CRITERIA**

Women who are between the ages of 35-65 who are able to participate in physical activity will be included in this study. Breast cancer survivors who were diagnosed with either unilateral or bilateral stage I-III cancer and have had surgical treatment at least 6 months prior to participation or women who have been diagnosed with symptomatic rotator cuff disease will be eligible. Women that are free of any upper limb impairments will be eligible for the control group. Individuals who have other health-related disorders, have other injuries to their upper extremity, back or neck or cannot raise their arms overhead will be excluded.

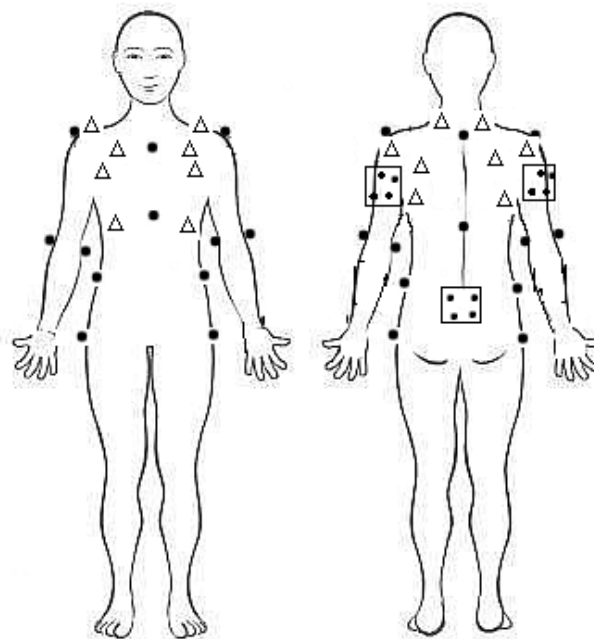
## **5. PROCEDURES**

The testing session for this study will be approximately 2.5 hours. During the session, you will be asked to perform selected tasks to evaluate upper limb movement. The procedures are as follows:

Once you have read and signed this informed consent form, you asked to complete four questionnaires: 1) the QuickDASH questionnaire which will evaluate your ability to use your upper limb and if there are any symptoms of disability present, 2) the Physical Activity Readiness Questionnaire (PAR-Q) to ensure you are able to safely participate in physical activities, 3) the FACT-B to determine quality of life ratings, and 4) a brief questionnaire about your employment status. These questionnaires will be used for secondary outcome measures and determine if you are eligible to participate in this study. If you are deemed ineligible by your responses to the questionnaires, the responses will be destroyed and you will not be asked to perform any of the following tests or tasks. Following the completion of the questionnaires, you will be asked to perform three common upper limb diagnostic tests (Neer's test, Hawkins test, and the empty can test) to determine the presence of any rotator cuff disease symptoms. These diagnostic tests will require you to elevate your arm while one of the researchers stabilizes your scapula or resists your upward motion to determine the presence of shoulder pain. Finally, your height, weight, upper arm length and lower arm length will be recorded.

Following the paperwork and initial measures, the preparation necessary for collecting the shoulder muscle activity and 3D upper body motion will be accomplished, i.e. positioning surface electrodes and reflective markers on your skin. Surface electrodes are small passive sensors that record muscle activity when affixed on the skin above muscles using tape. Prior to electrode placement, the skin overlaying the muscle belly will be shaved and cleansed with isopropyl alcohol. The EMG sensors will be placed on the shaved and cleansed skin over 6 bilateral upper limb muscles. Reflective markers are small reflective balls that are positioned on the skin using tape. The following figure show where the surface electrodes (triangles) and the reflective markers (black dots) will be positioned.

Before starting the trials, you will be asked to complete maximal voluntary contractions (MVC) for each of the muscles being collected. These contractions will be performed in positions chosen to elicit the highest possible activity for the desired muscle. One MVC (five seconds in duration) will be performed in each position, with at least two minutes between each exertion. There will be a total of 10 exertions. Each exertion will be performed against a dynamometers to simultaneously collect maximum force generation capacity.



After MVCs, the data collection protocol will begin. The protocol will begin with arm elevation in 3 planes. You will be asked to raise your arm as high as possible 3 elevations in each plane. You will have 6 seconds to complete the full raise and lower.

Following these elevations, you will perform an overhead reach and 3 reaching and dexterity tasks, which you will perform seated. The overhead reach will require you to reach to a shelf 1.5m off the ground with and without a weight and the repetitive reaching task will involve moving 30 marbles horizontally as quickly as possible. The fingertip dexterity task involves placing pins in a pegboard

as quickly as possible in the allotted time, while the hand and forearm dexterity task requires you to move blocks into a board in a predetermined pattern, as fast as you can. Both reaching tasks have 2 subtasks and the fingertip dexterity tasks has 3 subtasks. Each subtask will be repeated 3 times, for a total of 6 performance sets in each of the reaching tasks and 9 and 3 sets in the two dexterity tasks, respectively.

After these tests, you will stand up and perform an overhead lifting task. This task has 3 sets of 5 lifts at a weight that is approximately 50% of the maximum capacity from a previous collected normative dataset. The final task is the overhead work task which will require you to manipulate nuts and bolts at crown height while wearing 1 kg cuff weights. You will perform this task to voluntary maximum, meaning it will end when you can no longer perform the task. The final two tasks (overhead lift and overhead work) will involve a shelf that will be adjusted to the top of your head.

You will have rest breaks of at least one minute between sets and tasks to prevent fatigue. If you would like additional time in these breaks or additional rest breaks, please notify one of the research investigators and we would be happy to provide you with additional rest time.

With your permission, photos and videos may be taken during any point of the study for publication, teaching purposes or for presentation at scientific conferences. Your face will be blackened out in all images or video clips used and any other personal information will be removed that could be used to identify you.

## **6. POTENTIAL RISKS AND ASSOCIATED SAFEGUARDS**

As with any type of strenuous activity, there is a very small risk that the stress of performing exercise will cause heart rhythm abnormalities, chest discomfort or lightheadedness. People with a history or presence of significant cardiac (heart) disease, heart rhythm disorders, or currently pregnant should not participate in this study. The PAR-Q that will be administered before the test session is a screening tool to determine if you can safely participate in the physical tasks that are a part of this study. It is also important that you report any pain, discomfort, fatigue or other symptoms that you might have during the exercise test to the study staff in attendance. Some participants may experience muscle pain or discomfort due to the overhead the tasks, but this should be temporary and will disappear after a few days.

At least one of the investigators present will be trained in CPR and First Aid to deal with any potential problems that may arise. All tests can be terminated by you at any point if you are feeling any pain or discomfort. A spotter will be present at all times and you will be closely monitored, especially in the overhead lift and overhead work. Additionally, all equipment will be cleaned with an alcohol based sanitizer. If you have an allergy or sensitivity to adhesives, you should consider not participating.

In the unlikely event of an adverse effect arising related to the study procedures, necessary medical treatment will be made available at no additional cost to you. As soon as possible, notify the research team. By signing this document, you do not waive any of your legal rights.

#### **7. COST OF PARTICIPATION**

You will not be charged for any research-related procedures. You will not be paid for participating in this study. You will not receive any compensation, or financial benefits for being in this study, or as a result of data obtained from research conducted under this study.

#### **8. POTENTIAL BENEFITS OF PARTICIPATION**

If you choose to participate in this study, you may or may not experience any benefits. You may find benefit by receiving a summary of your data. The knowledge gained from this research may assist in rehabilitation and return to work recommendations for breast cancer survivors. We plan to share significant findings to doctors and physiotherapists to help improve the assessment and treatment of breast cancer survivors.

#### **9. CONFIDENTIALITY AND SECURITY OF DATA**

A numerical code will be associated with your name; no personal identifiers will be used with your study data. The numerical code will be used with the questionnaires and digital recordings. Your name will not be associated with the recording. All data will be stored for 5 years on computer hard drives (password protected) and/or digital storage media, after which it will be permanently deleted. Consent forms and questionnaires will be stored separately in a locked filing cabinet in Health Sciences E-wing Room 3405 for 5 years, after which they will be discarded. The principal investigator, Dr. Milosavljevic, will be responsible for this data. Research records identifying you may be inspected by the University of Saskatchewan Biomedical Research Ethics Board in the presence of the Principal Investigator for quality assurance and monitoring purposes. Only grouped results will be included in publications and reports, i.e. no individual data. This grouped data will be analyzed and used to address three specific objectives for Angelica's PhD thesis, including use in both a musculoskeletal and statistical model.

#### **10. CHANGING YOUR MIND ABOUT PARTICIPATION**

If you choose to enter the study and then decide to withdraw later, all data collected about you during your enrolment will be retained for analysis.

#### **11. CONCERNS ABOUT PARTICIPATION**

We would like to assure you that this study has been reviewed by, and received ethics clearance through a University of Saskatchewan Research Ethics Committee. However, the final decision about participation is yours. In the event you have any comments or concerns resulting from your participation in this study, please contact the Chair of the University of Saskatchewan Research Ethics Board, at 306-966-2975 (out of town calls 1-888-966-2975). The Research Ethics Board is a group of individuals (scientists, physicians, ethicists, lawyers and members of the community) that provide an independent review of human research studies. This study has been reviewed and approved on ethical grounds by the University of Saskatchewan Research Ethics Board.

## 12. QUESTIONS ABOUT THE STUDY

If you have any further questions or want any other information about this study, please feel free to contact Angelica Lang, Dr. Soo Kim, or Dr. Stephan Milosavljevic.

Sincerely Yours,

Angelica Lang  
Ph.D Student  
Department of Health  
Sciences  
University of Saskatchewan  
[angelica.lang@usask.ca](mailto:angelica.lang@usask.ca)

Soo Kim, Ph. D.  
Associate Professor  
School of Physical Therapy  
University of Saskatchewan  
306-966-8399  
[soo.kim@usask.ca](mailto:soo.kim@usask.ca)

Stephan Milosavljevic, Ph. D.  
Professor/Director  
School of Physical Therapy  
University of Saskatchewan  
306-966-8655  
[stephan.milosavljevic@usask.ca](mailto:stephan.milosavljevic@usask.ca)

## CONSENT OF PARTICIPATION

**Project Title: Towards improved clinical evaluation of the shoulder: defining upper limb motion of breast cancer survivors during functional evaluation tasks**

**Student Investigator: Angelica Lang**

**Faculty Supervisor: Drs. Stephan Milosavljevic, Soo Kim, and Clark Dickerson**

By signing this document, I am confirming that:

- I have read the information in this consent form.
- I understand the purpose and procedures and the possible risks and benefits of the study.
- I was given sufficient time to think about it.
- I had the opportunity to ask questions and have received satisfactory answers.
- I am free to withdraw from this study at any time for any reason and the decision to stop taking part will not affect my future medical care.
- I agree to tell the study doctor at once if I feel I have had any unexpected or unusual symptoms.
- I understand that this study will not provide any benefits to me.
- I give permission for the use and disclosure of my de-identified personal health information collected for the research purposes described in this form.
- I give permission for the access of my identifiable personal health information for the research purposes described in this form.
- I understand that by signing this document I do not waive any of my legal rights.
- I understand I will be given a signed and dated copy of this consent form.
- 

Participant Name: \_\_\_\_\_ (Please print)

Participant Signature: \_\_\_\_\_

Person Obtaining Consent Name: \_\_\_\_\_ (Please print)

Person Obtaining Consent Signature: \_\_\_\_\_

Date: \_\_\_\_\_

**CONSENT TO USE PHOTOGRAPHS AND VIDEOS IN TEACHING,  
PRESENTATIONS, and/or PUBLICATIONS**

**Project Title: Towards improved clinical evaluation of the shoulder: defining upper limb motion of breast cancer survivors during functional evaluation tasks**

**Student Investigator: Angelica Lang**

**Faculty Supervisor: Drs. Stephan Milosavljevic, Soo Kim, and Clark Dickerson**

Sometimes certain photographs and videos clearly demonstrate a particular feature or detail that would be helpful in teaching or when presenting the study results at a scientific conference or in a publication.

I agree to allow photographs, videos and/or quotations that were captured during my participation in the study to be used in teaching, scientific presentations and/or publications with the understanding that my identity will not be disclosed. Any identifying information captured in a photograph and/or video will be blackened out and any quotations will remain anonymous and will not be linked to myself in any way.

***Participant's Name (Please Print):*** \_\_\_\_\_

***Participant's Signature:*** \_\_\_\_\_

***Date:*** \_\_\_\_\_

***Person Obtaining Consent:***

\_\_\_\_\_



## APPENDIX C: QUICK DISABILITIES OF ARM, SHOULDER AND HAND (QuickDASH)



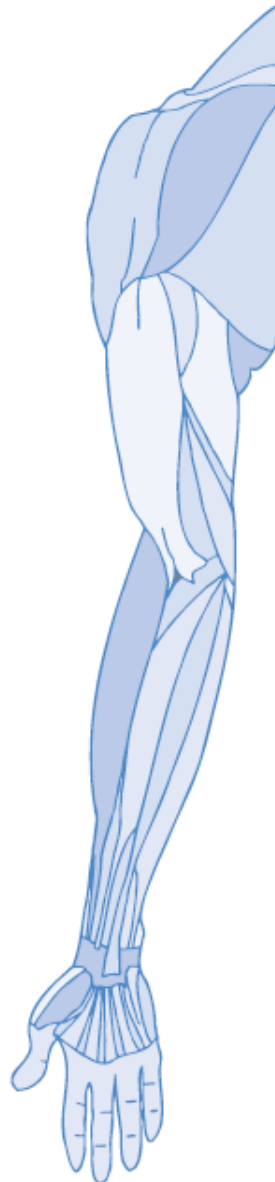
### INSTRUCTIONS

This questionnaire asks about your symptoms as well as your ability to perform certain activities.

Please answer *every question*, based on your condition in the last week, by circling the appropriate number.

If you did not have the opportunity to perform an activity in the past week, please make your *best estimate* of which response would be the most accurate.

It doesn't matter which hand or arm you use to perform the activity; please answer based on your ability regardless of how you perform the task.



## QuickDASH

Please rate your ability to do the following activities in the last week by circling the number below the appropriate response.

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	UNABLE
1. Open a tight or new jar.	1	2	3	4	5
2. Do heavy household chores (e.g., wash walls, floors).	1	2	3	4	5
3. Carry a shopping bag or briefcase.	1	2	3	4	5
4. Wash your back.	1	2	3	4	5
5. Use a knife to cut food.	1	2	3	4	5
6. Recreational activities in which you take some force or impact through your arm, shoulder or hand (e.g., golf, hammering, tennis, etc.).	1	2	3	4	5

	NOT AT ALL	SLIGHTLY	MODERATELY	QUITE A BIT	EXTREMELY
7. During the past week, to what extent has your arm, shoulder or hand problem interfered with your normal social activities with family, friends, neighbours or groups?	1	2	3	4	5

	NOT LIMITED AT ALL	SLIGHTLY LIMITED	MODERATELY LIMITED	VERY LIMITED	UNABLE
8. During the past week, were you limited in your work or other regular daily activities as a result of your arm, shoulder or hand problem?	1	2	3	4	5

Please rate the severity of the following symptoms in the last week. (circle number)

	NONE	MILD	MODERATE	SEVERE	EXTREME
9. Arm, shoulder or hand pain.	1	2	3	4	5
10. Tingling (pins and needles) in your arm, shoulder or hand.	1	2	3	4	5

	NO DIFFICULTY	MILD DIFFICULTY	MODERATE DIFFICULTY	SEVERE DIFFICULTY	SO MUCH DIFFICULTY THAT I CAN'T SLEEP
11. During the past week, how much difficulty have you had sleeping because of the pain in your arm, shoulder or hand? (circle number)	1	2	3	4	5

QuickDASH DISABILITY/SYMPTOM SCORE =  $\left( \frac{\text{sum of } n \text{ responses}}{n} - 1 \right) \times 25$ , where n is equal to the number of completed responses.

A QuickDASH score may not be calculated if there is greater than 1 missing item.